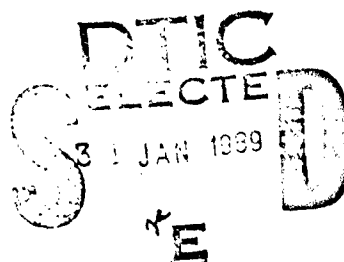AD-A203 615

IDA REPORT R-338

THE ROLE OF CONCURRENT ENGINEERING IN WEAPONS SYSTEM ACQUISITION

Robert I. Winner
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Harold E. Bertrand
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The purpose of this IDA Report is to document the results of a study made by the Institute for Defense Analyses (IDA) for the Department of Defense to assess claims of improved competitiveness in the commercial industrial base resulting from the use of *concurrent engineering*. IDA reviewed published documentation on concurrent engineering and its implementation in industry; conducted workshops to learn from industry of the various approaches being taken to increase competitiveness; and visited and held technical discussions with 14 major U.S. corporations on their successful experiences with the use of concurrent engineering. The IDA Report is the IDA study team's judgment of the consensus expressed by the groups of recognized experts.

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INSTITUTE FOR DEFENSE ANALYSES

EXECUTIVE SUMMARY

The Department of Defense (DoD) tasked the Institute for Defense Analyses (IDA) to assess claims of improved product quality at lower costs and shortened product development time through the use of *concurrent engineering*. Specifically, IDA was tasked to determine whether the publicized benefits were typical of those achieved by others who tried concurrent engineering; whether DoD could expect similar results if defense contractors implemented concurrent engineering in the weapons system acquisition process; and what had to be done to encourage defense contractors to use concurrent engineering.

The IDA study team reviewed published reports and papers on concurrent engineering and its implementation in industry; held discussions with manufacturing experts in government, industry, and academia; conducted workshops to learn about the various approaches being taken to apply concurrent engineering in industry. The team visited and held technical discussions with fourteen major U.S. corporations.

The report that follows documents the IDA study team's assessment of the views that were expressed. This report is based on a "case study" approach. Therefore, it does not provide an unbiased quantitative assessment of costs and benefits. The report's qualitative assessment and recommendations provide a first step in developing such information.

WHAT IS CONCURRENT ENGINEERING?

The basic principle of concurrent engineering—the integration of product and process design—is not new. As a common sense approach to product development, it has been known for some time. Modern techniques have facilitated the use of concurrent engineering, but its application within the United States is still in its infancy.

This report provides an initial description of the practice, and reported benefits of concurrent engineering. It is anticipated that more complete models describing the functions and information exchanges of concurrent engineering will be developed in subsequent studies. The following definition of concurrent engineering is used in this report:

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.

This management, engineering, and business approach integrates the design of a product and its manufacturing and support processes. Its implementation takes a variety of forms and uses different methods and techniques; however, there are generic elements:

• Reliance on multifunction teams to integrate the designs of a product and its manufacturing and support processes.

- Use of computer-aided design, engineering, and manufacturing methods (CAD/CAE/CAM) to support design integration through shared product and process models and data bases.

- Use of a variety of analytical methods to optimize a product's design and its manufacturing and support processes.

The IDA study team observed industry using concurrent engineering on products ranging from digital communication switches to mainframe computers to mobile missile launch vehicles.

WHAT IS CONCURRENT ENGINEERING'S VALUE?

Companies reported that over a period of years, procedures that were originally instituted to identify and solve problems became so complex that their effect was to impede product development.

The President's Blue Ribbon Commission on Defense Management (Packard Commission) notes the increasing complexity of federal law governing acquisition, the growing bureaucracy of the acquisition system, and the decreasing productivity of acquisition management as a result of greater encumbrance. Starting in the late 1950s and early 1960s, the DoD instituted a variety of initiatives, procedures, specifications, and policies designed to improve weapons system quality while controlling budget and schedule risk. The result today is a system that the Commission characterized as beset by duplicative functions, excessive regulations, and fragmented responsibility. Concurrent engineering is one of the tools that can be used to improve the DoD acquisition process.

Reported benefits attributed to concurrent engineering included:

- Improving the quality of designs which resulted in dramatic reductions of engineering change orders (greater than 50 percent) in early production.

- Product development cycle time reduced by as much as 40 to 60 percent through the concurrent, rather than sequential, design of product and processes.

- Manufacturing costs reduced by as much as 30 to 40 percent by having multifunction teams integrate product and process designs.

- Scrap and rework reduced by as much as 75 percent through product and process design optimization.

Collectively, the concurrent engineering disciplines that require the early consideration of a product's manufacturing and support process while shaping the user's requirements into a product's design were reported to result in a higher quality design.

PRINCIPAL FINDINGS

- Companies that have implemented concurrent engineering report that they are producing higher quality products at lower cost and in less time than they were able to previously.

- Significant cultural and management changes underly the successful implementation of concurrent engineering. As a consequence, considerable time (2-4 years) is often needed before benefits are realized from concurrent engineering.

- Concurrent engineering requires top-down leadership and involvement to succeed with continual reinforcement through training, backing, interest, and dialogue throughout the total weapons system acquisition process.

- While the understanding of concurrent engineering is continuing to emerge, and its boundaries are not yet fully defined, many of the methods and technologies to implement its central elements exist today.

- Significant differences exist between the commercial marketplace and the DoD domain. Despite these differences, case studies of the implementation of concurrent engineering by several defense contractors suggest that concurrent engineering can be successfully applied in the DoD environment.

- There are DoD policies, management procedures, contracting methods, and regulations that could inhibit the successful implementation of concurrent engineering within DoD.

- DoD participation in the development or improvement of enabling methods and technologies of concurrent engineering can assist in ensuring that it can be applied to the unique aspects of weapon system procurements.

RECOMMENDATIONS

- The Department of Defense should take positive steps to encourage the use of concurrent engineering in weapons system acquisitions. Appropriate steps include:

  — OSD's principal acquisition managers should adopt concurrent engineering as a key implementation mechanism for total quality management (TQM). (A starting point for a policy letter is presented in Appendix E of this report.)

  — DoD's principal acquisition managers should make concurrent engineering a prominent part of their dialogue with their contractor base.

  — DoD and the Services should jointly identify pilot programs for the purpose of demonstrating ways to implement concurrent engineering in weapons system procurements, to identify and eliminate barriers to concurrent engineering within DoD, and to evaluate the benefits.

- In parallel with the above, DoD should take steps to support the cultural and management changes necessary to gain the full potential benefits of concurrent engineering. These supporting steps include:

  — DoD should implement an education and training program that starts with the senior OSD acquisition managers and progresses to all levels of DoD's acquisition organization.

  — DoD should develop and improve the methods and technologies specifically required to support the use of concurrent engineering in weapons system acquisition programs.

— The DoD should expand upon the beneficial aspects of existing DoD manufacturing improvement initiatives to incorporate and support the concepts of concurrent engineering. These initiatives include, but are not limited to, MANTECH, IMIP, MANPRINT, and Transition-To-Production Templates.

— OSD acquisition managers should initiate a process that involves DoD contractors and subcontractors to identify the policies, rules, regulations, directives, procedures, and practices that act, or are seen to act, as barriers or inhibitors to industries' use of concurrent engineering in weapons system procurements. Unless overriding considerations exist, OSD should take the necessary actions to remove or lessen the impact of such barriers.

ACRONYMS

ANOVA	Analysis of Variation
ANS	American National Standards
ASD	Aeronautical Systems Division
ASI	American Supplier Institute
CALS	Computer-Aided Logistics Support
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CFD	Computational Fluid Dynamics
CUSUM	Cumulative Sum
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
EIS	Engineering Information System
EVOP	Evolutionary Operation
EWMA	Exponentially Weighted Moving Average
EC	Engineering Changes
FEM	Finite Element Models
FMEA	Failure Mode Effects Analysis
FSD	Full Scale Development
FTA	Fault Tree Analysis
GMAP	Geometric Modeling Application Program
IDA	Institute for Defense Analyses
JTAG	Joint Test Action Group
LCC	Life-Cycle Cost
LSSD	Level Sense Scan Device
MANTECH	Manufacturing Technology
MDAC	McDonnell Douglas Astronautics Corporation
OSD	Office of the Secretary of Defense
PDDI	Product Data Description Interface
PDES	Product Description Exchange Standard
PMT	Physical Mechanical and Thermal
QFD	Quality Function Deployment
R&M	Reliability and Maintainability
RAMCAD	Reliability and Maintainability Computer-Aided Design
RFP	Request for Proposal
RISC	Reduced Instruction Set Computer
SEI	Software Engineering Institute
SMT	Surface Mount Technology
SOW	Statement of Work
SPC	Statistical Process Control

ACRONYMS

SRAM	Short Range Air-to-Ground Missile
TBD	To Be Determined
TCF	Total Concept Facility
TISSS	Tester Independent Support Software System
TQM	Total Quality Management
TWT	Traveling-wave Tube
ULCE	Unified Life Cycle Engineering
USD(A)	Under Secretary of Defense for Acquisition
VHDL	VHSIC Hardware Design Language
VHSIC	Very High Speed Integrated Circuit
VLSI	Very Large Scale Integration

PREFACE

8-/ 0031

Task Order T-B5-602, under contract MDA903- J-C-0007, directs the Institute for Defense Analyses to identify critical information and factors associated with the use of concurrent engineering in weapons system development as well as DoD and industry efforts that are potentially applicable to this effort. This report responds to a subtask that calls for a report based on the findings of a study of concurrent engineering including site visits to companies practicing it and is intended to be part of a larger effort. It contains a straw man approach to achieving concurrent engineering in weapons system development (Appendices D and E).

This report has been prepared by an IDA study team (the authors of this document) based on a preliminary study of concurrent engineering. The practice of concurrent engineering in the United States is an emerging discipline and validated models describing the functions and information requirements have not yet been developed. This report represents an initial attempt to define a conceptual framework for concurrent engineering, to describe the methods and techniques being used by those practicing it, and to list reported benefits of those attempts. It is anticipated that more complete models describing the functions and information exchanges of concurrent engineering will be developed in subsequent studies.

In preparing this report, the study team gathered information from individual industrial, academic, and corporate experts and from experienced corporations. The study team organized the information and made judgments about the validity and applicability of data and expert opinion. This report is based on those judgments.

The report was reviewed by internal and external panels whose members are listed in Appendix H. Workshop participants are listed in Appendix F. The contribution of participants and reviewers has been substantial, but inclusion of their names should not be construed as an endorsement of this report.

The authors acknowledge the contributions of many who helped to produce this report: the companies who provided success stories, the speakers at the workshops, and the workshop attendees who helped to shape the ideas presented in this report. This report would not be possible without their assistance and the support of their parent companies.

The study team especially acknowledges the contributions of Gary Ammerman, Charlie Bernstein, George Box, Don Clausing, Travis Engen, Alan Fulton, Larry Griffin, Istvan Gorog, George Gregurec, John Halpin, Bill Haney, Leo Hannifin, Bill Henry, Stuart Hunter, Ed Istvan, Chuck Laurenson, Vern Menker, James Nevins, Mike Patterson, Madhav Phadke, Jim Pratt, Homer Sarasohn, Bob Scheli, Gene Seefeldt, John Sheridan, Russell Shorey, Don Snyder, and Michael Watts.

The authors also express their thanks for the help they received from Helen Singleton, Diane Eason, and Chloie Boelte, as well as the editing assistance from Ellen Pennell and Katydean Price.

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The Role of Concurrent Engineering in Weapons System Acquisition

1. INTRODUCTION AND SUMMARY

This report provides information for senior Department of Defense executives on how a management and engineering philosophy called concurrent engineering might be applied to the task of improving the quality, decreasing the cost, and reducing the time to develop and deploy weapons systems. It describes changes in engineering and management procedures as well as critical information handling methods that have been used in thirteen diverse companies[1] to simultaneously achieve these goals. It provides recommendations for using concurrent engineering in the weapons system acquisition process[2] to promote corresponding results. Although the reported results are encouraging and the improvements appear to be necessary, reports indicate that carrying out the recommended changes will be a demanding challenge.

The President's Blue Ribbon Commission on Defense Management noted that weapons systems take too long to develop, cost too much to produce, and often do not perform as promised or expected.[3] Similar problems in automobile and electronics industries resulted in a crippling loss of market share by United States producers to offshore competition. Surviving companies in affected industries responded to competitive pressures by modifying their management, engineering, production, and customer support processes. Many of the modifications included a more systematic method of concurrently designing both the product and the downstream processes for producing and supporting it. This systematic approach is the fundamental theme of concurrent engineering.

In response to initial reports from several companies, the Under Secretary of Defense for Acquisition (USD(A)) directed that the Institute for Defense Analyses (IDA) investigate concurrent engineering and its possible application to weapons system acquisition. This report presents the results of the first phase of this analysis and is based on the IDA study team's initial contact with companies that have claimed success in using concurrent engineering or elements of it.

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1. Case studies of the application of elements of concurrent engineering within AT&T, Aerojet Ordnance, Boeing, Deere, Grumman, Hewlett-Packard, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments are included in Appendix A. Information about Ford and Allied-Signal is cited in the body of the report.

2. In this report the terms "weapons system acquisition process" and "acquisition process" are used synonymously.

3. *A Quest For Excellence*, Final Report to the President by the President's Blue Ribbon Commission on Defense Management, June 1986, p. xxii.

The claims are impressive. The products considered range from mainframe computers and digital communication switches to missile-launch vehicles and construction equipment. Reported results include reduction of development cycles by as much as 50 percent. Savings of 30 percent from part-count improvement, better use of existing facilities, and reduction of scrap and rework have been documented. In addition to electronics, vehicles, and construction equipment, reports of significant improvements in nuclear power programs, missile production, missile launcher design, pyrotechnics, and aircraft design and manufacture were also presented. The quality of the designs (as measured by the number of engineering changes in early production, and changes caused by design errors) has improved by a factor of two. Production quality improvements are reflected in the cost of inspection, scrap, and rework. The study team relied on data gathered from reports from members of these companies, published reports of similar successes, and personal visits. This study relies on the team's assessment of this data and judgments about the validity and applicability of data and expert opinion. Table 1 shows a sample of the reported benefits of using new methods in six companies.

Each situation cited in this report has unique features and may be described within the individual company by different names. There is a common theme of systematic, concurrent activity among several engineering disciplines, and the term *concurrent engineering* is used to describe it. *Concurrent engineering* is defined as follows:

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.

People from industry who participated in IDA's workshops and whose companies experienced success with concurrent engineering are enthusiastic about their newly found engineering and production methods. They report improved quality of their products and services, decreased costs, and improved adherence to shorter schedules. They claim that their companies are becoming more competitive and more confident. They acknowledge that their accomplishments are the result of hard work and emotionally difficult changes—organizational realignment, new concepts in evaluation of people and functions, and rediscovery of the paramount role of product and process quality to name but a few. The changes are sometimes described as *corporate renewal*. Two years is about the time needed to begin to produce results from such efforts. After four years, participants frequently predict even greater improvements lie ahead. They admit to mistakes and false starts, but

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™ 5ESS is a trademark of AT&T.

TABLE 1. Cost, Schedule, and Quality Benefits

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% savings on bid for reactor and missile projects.	Significant savings (reduction from 45 weeks to 8 hours) in one phase of high-speed vehicle preliminary design; 18 month saving on TAV-4B design.	Scrap reduced 58%, rework cost reduced 29%, and nonconformances reduced 38%; weld defects per unit decreased 70%; 68% fewer changes on reactor; 68% lower drawing changes on TAV-4B.
Boeing Ballistic Systems Division	Reduced labor rates by $25/hour; savings 30% below bid.	Part and materials lead-time reduced by 30%; one part of design analysis reduced by over 90%.	Floor inspection ratio decreased by over 2/3; material shortages reduced from 12% to 0; 99% defect-free operation.
AT&T	Cost of repair for new circuit pack production cut at least 40%.	Total process time reduced to 46% of baseline for 5ESS.	Defects reduced by 30% to 87%.
Deere & Company	30% actual savings in development cost for construction equipment.	60% savings in development time.	Number of inspectors reduced by 2/3.
Hewlett-Packard Co. Instrument Division	Manufacturing costs reduced 42%.	Reduced development cycle time 35%.	Product field failure rate reduced 60%. Scrap and rework reduced 75%.
IBM	Product direct assembly labor hours reduced 45%.	Significant reduction in length of PMT design cycle. 40% reduction in electronic design cycle.	Fewer engineering changes. Guaranteed producibility and testability.

they are convinced that their company's survival depends on such continued improvement.

The importance of improving quality is a recurring theme among the companies visited. Quality is no longer seen as something to be added onto a product, or something achieved through inspection at the end of the line. Quality is now seen as a driver for achieving lower costs and shorter schedules. Companies report that improving quality allows them to eliminate many inspections, reduce scrap and rework, improve performance and reliability, and reduce unit as well as life-cycle cost.

Some of the concurrent engineering success stories are taken from actual weapons system development projects. Based on evaluating this evidence and considering the range of other applications, the study team believes that concurrent engineering can be applied in the acquisition process and that it will provide better quality goods and services in less time and at lower cost. The study team also believes that now is an opportune time to use industry's enthusiasm for improved practices and the public perception that change in the acquisition process is needed, in order to supply the motivation to improve the acquisition process.

A view commonly held by those who reported success with concurrent engineering is that successful change depends on sustained upper management leadership. They assert that this leadership must establish a total quality management environment. In such an environment, quality improvement is reported to drive down both unit and life cycle costs and to shorten schedules. This counterintuitive result has been achieved through the reduction of test analyze and fix, inspection, rework, and scrap.

Given these results and in response to the task order for this study, this report presents recommendations regarding the adoption of concurrent engineering in the weapons system acquisition process.

2. APPROACH

2.1 Background

The Department of Defense maintains a continuing interest in the competitiveness of the industrial base because that competitiveness affects the ability of the Department to equip the military forces. Within the last decade, the ability of some U.S. industries to compete has been questioned. Since the early 1980s, several companies have reported that they have been able to compete more effectively because they have implemented a range of new practices, including concurrent engineering.

The Under Secretary of Defense for Acquisition (USD(A)) directed that the Institute for Defense Analyses investigate concurrent engineering and its possible application to weapons system acquisitions. This report presents the results of the first phase of that analysis and is based on the IDA study team's contact with the companies that claimed success in using concurrent engineering, or elements of it.

2.2 Objective

The study team organized the information gathered during the first phase of the study and made judgments about the validity and applicability of data and expert opinion. This report is based on those judgments. In response to the tasking, it presents a recommended approach for achieving concurrent engineering in weapons system development.[4] To support the recommendations, this report describes what is meant by concurrent engineering and shows how it should help the DoD meet its goal of simultaneously decreasing unit and life-cycle costs, decreasing time to deployment, and increasing adherence to desired functionality of weapons systems. Subsequent phases of the task will address the remaining task objectives.

2.3 Scope

This study has concentrated on engineering approaches, technologies, and related management practices that can support or enhance concurrent engineering. In terms of the acquisition process, the report addresses those activities that normally occur with Milestone 0 (Program Initiation) and continue through the life of the weapons system.

A range of activities is needed to improve the weapons system acquisition process. Concurrent engineering relies on many of them for its success. For example, continued support is needed in areas such as basic research in science and engineering; improved management and leadership; revitalized industrial capabilities; and improved cooperation among the military in defining operational needs. While recognizing the importance of these activities, the present report is primarily concerned with concurrent engineering.

The workshop participants identified many perceived barriers within the acquisition process to the adoption of concurrent engineering. The study group did not make the

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4. Subtask 4.e of the statement of work contained in the task order.

identification or elimination of such barriers a major topic of the report because a related effort is addressing the barrier question. The IDA study team followed the progress of a closely related group that presented insights from a cross section of industrial officials regarding concurrent engineering, particularly senior management's perception of barriers and incentives to implementation.[5] The current report, while acknowledging the importance of such efforts, focuses on a narrower segment of the problem, namely the engineering tasks associated with concurrently designing the product and related processes.

One particular related effort, Total Quality Management, was frequently mentioned by participants. The study team believes that an effort to deploy concurrent engineering in weapons system acquisition is consistent with the Total Quality Management Initiative (TQM).[6] The TQM initiative can be viewed as an umbrella effort under which concurrent engineering is a key implementation mechanism. Without the emphasis on quality that characterizes TQM, concurrent engineering will not achieve its goals. In fact, every company visited during this study has either begun to implement its own TQM program or has developed an in-house quality improvement program that is basically equivalent.

2.4 Methodology

2.4.1 Overview

This report describes concurrent engineering in terms of success stories that appeared in the literature, were presented at workshops, or were discussed during site visits. Presentations of various researchers describing efforts designed to facilitate the practice of concurrent engineering and technical working groups from government, academia, and industry helped the study team form a conceptual framework for relating technology needs to DoD goals. The study team organized the information gathered during the study and made judgments about the validity and applicability of data and expert opinion. This report is based on those judgments.

The IDA study team investigated reports of companies that simultaneously improved quality, decreased cost, and reduced development time through the application of concurrent engineering. Workshops of moderate size, 60 to 80 participants,[7] were convened to discuss concurrent engineering. The participants were chosen to obtain a cross section of engineering, production, computer support, research, and government perspectives. Participants with business interests in the commercial sector, the defense sector, and in both sectors were invited.

At the initial meeting, several speakers presented descriptions of successful approaches within their companies. The presentations were informative, but indicated the need for more

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5. *Industrial Insights on the DoD Concurrent Engineering Program*, The Pymatuning Group, Inc. (October 1988).

6. Secretary of Defense Memorandum of 30 March 1988, Subject: "Department of Defense Posture on Quality."

7. Appendix F provides a listing of the participants and their affiliations.

detailed discussions between the IDA study group and the respective companies. Accordingly, site visits were arranged to provide the study group with a better understanding of the various approaches to concurrent engineering. The success stories that resulted from those visits are included in Appendix A and (along with the results of several workshops, research, and follow-up discussions) form the basis for the findings and recommendations.[8]

There are no stories of failures of concurrent engineering because none were presented by any of the participants either publically or in private discussions. There were initial failures associated with attempts to apply some of the methods or technologies associated with concurrent engineering. However, the companies that reported the initial problems said that they analyzed the causes of the difficulties, revised their approaches, and went on to achieve their goals. Despite requests by the study team, no one came forward with a case of concurrent engineering being tried and failing to reduce cost, improve quality, or shorten the schedule. This does not imply that failures do not exist, but rather that the study team did not find specific examples.

2.4.2 Method of Investigation—Details

The findings and recommendations presented herein are based on the first-hand accounts of people who used some elements of concurrent engineering and experienced a significant measure of success. The study of concurrent engineering began with a review of the pertinent literature to identify the issues and the experts in the field. The IDA study group reviewed the results from the Defense Advanced Research Projects Agency (DARPA) Concurrent Engineering Workshop of December 1987. The study group contacted many of the experts and sponsored several workshops in which they presented ideas connected with concurrent engineering. In addition, representatives from various DoD organizations either made presentations or participated in panels to describe their thoughts on the subject.

From these workshops, the IDA study team identified a list of corporations[9] where further discussion of concurrent engineering experience was expected to be profitable. Teams from IDA made one or two-day visits to these companies. There were also continuing discussions with industrial and academic experts and interested parties in DoD. The study group applied their own expertise and judgment in exploring concurrent engineering. On the basis of this, the study group gained useful insights into the use of concurrent engineering, its applicability in weapon system acquisition, and the surrounding issues presented in this report.

Some critics point out that favorable results in commercial ventures do not ensure similar effects in the DoD domain. Their objections are based on four significant differences between commercial products and weapons systems: 1) weapons systems are more complex, 2) the requirements for weapons systems are not well defined, 3) weapons systems

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8. The data presented by the companies during the visits is taken at face value. A separate task to evaluate cost/benefit measures related to concurrent engineering has been assigned to IDA.

9. IDA visited McDonnell Douglas, AT&T, Texas Instruments, ITT, Boeing, Deere, Northrop, and IBM.

incorporate the latest advances in technology for which validated models of behavior do not exist, and 4) contracting methods and acquisition regulations that control weapons system procurement are the result of political as well as economic processes (there are fewer incentives to reduce costs or to deliver a product early).[10] Critics also point out that while all program managers ostensibly want to reduce costs and deliver earlier, they are pressured by risk avoidance to extend development life cycles as long as possible.

A previous study of weapons acquisition used computers, electronic switches, and commercial aircraft as examples of products with complexity that is comparable to that of weapons systems.[11] This analysis adopts the same paradigm regarding the question of complexity. Analyses to date show that concurrency of system design with design of processes for production and support will identify requirements features that are candidates for trade-off, but the decision to make those trade-offs (conflicting requirements) is beyond the scope of this report.

The study team acknowledges the unique problems of defining requirements for weapons systems as compared to requirements for commercial products. However, the methods used by the Services to determine and validate requirements are not within the scope of the current task.

2.4.3 Workshops

IDA convened two workshops during May 1988. The first was held on 11 and 12 May. Participants met to define concurrent engineering and to describe how companies were using concurrent engineering techniques. A second workshop on 25 and 26 May served to provide additional examples and to identify specific management and technology issues. Appendix E lists the titles of presentations at both workshops and the names and affiliation of the presenters.

The final phase one workshop was held September 14 and 15, 1988, to provide a review of a draft version of this report by the people who helped gather the information.

2.4.4 Site Visits

During June, July, and August, team members from IDA visited eight locations for additional discussions concerning concurrent engineering. The discussions focused on reasons for introducing improved engineering and production methods, problems encountered in introducing the changes, and the results. The case studies in Appendix A are drawn from these discussions. Because they are based on actual experiences of companies engaged in competitive markets, not on responses to directed DoD programs, the case studies may seem to be only partially related to concurrent engineering. Despite this, they

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10. Other differences include long-term responsibility for the cost of support and maintenance and the need for configuration management.

11. See *A Quest for Excellence*, Final Report to the President by the Blue Ribbon Commission on Defense Management, June 1986.

are descriptions of the elements of concurrent engineering being applied by some of the most successful companies in the United States.

2.5 Structure of the Report

Section 3 is a discussion of concurrent engineering: what it is—and is not. It includes the characteristics of the process, benefits, applicability to the acquisition process, and its relationship to existing initiatives. Several issues are raised in this section. Section 4 describes a conceptual framework for concurrent engineering. Section 5 contains the principal findings and discusses key issues. Section 6 sets forth recommendations for deploying concurrent engineering and sustaining continuous improvements in the engineering of weapons systems.

The appendices contain supporting details. Appendix A describes the case studies that form the basis for many of the findings. Appendix B is a high-level description of the techniques cited in the case studies. Appendix C presents a detailed description of the conceptual framework introduced in Section 4. This detail can be used to develop a technology development and deployment plan. Appendix D provides a more detailed mapping of concurrent engineering onto the acquisition process. Appendix E is a sample policy statement regarding concurrent engineering within the DoD. Appendix F is a listing of workshop participants and reviewers of this report. Appendix G is a catalogue of the titles and speakers from the first two workshops. Appendix H lists the internal and external reviewers for this report.

3. CONCURRENT ENGINEERING

This section sets forth a definition of concurrent engineering, describes the characteristics of companies that practice it, summarizes their reported accomplishments, shows how it fits in the acquisition process, and relates it to other DoD initiatives.

3.1 Definition

Participants at the first IDA concurrent engineering workshop discussed concurrent engineering practices in several U.S. companies. They described the use of methods that included traditional system engineering practices and new engineering and management approaches. DoD and Air Force initiatives to improve the acquisition process were also presented. Based on the discussion at that workshop, on further contributions from participants, and consultation with various reviewers, the following definition was developed:

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.

Concurrent engineering is characterized by focus on the customer's requirements and priorities, a conviction that quality is the result of improving a process, and a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise. The philosophy of concurrent engineering is not new. The terms "system engineering", "simultaneous engineering", and "producibility engineering" have been used to describe similar approaches. In fact, a number of authors have described similar techniques and hundreds of companies have applied them successfully. Nevertheless, many companies have *not* adopted concurrent engineering because of the "fundamental, wrenching, far-reaching transformations that are required throughout the enterprise."[12]

The integrated, concurrent design of the product and processes is the key to concurrent engineering. Figure 1 compares a sequential approach to product development at the top, with a concurrent approach in the lower half. In the sequential method, information flows are intended to be in one direction, from left to right as shown by the arrows. In the concurrent approach, information flows are bi-directional and decisions are based on consideration of downstream as well as upstream inputs. The companies studied in this report found that achieving this sharing of information required both organizational and technological change.

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12. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), p 344.

Sequential Engineering

Requirement Product Development Process Development Prototype

$\longrightarrow$ $\longrightarrow$ $\longrightarrow$

Concurrent Engineering

Requirement

Product Development

Process Development

Prototype
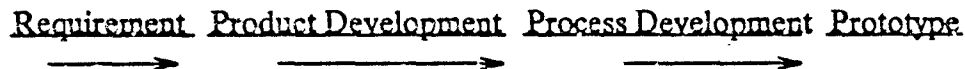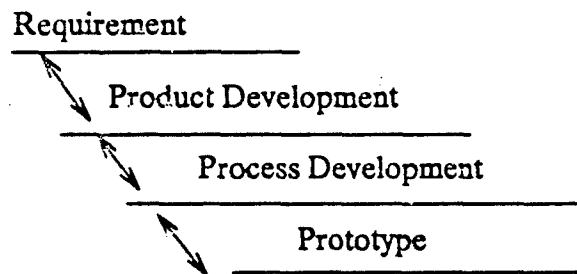
Figure 1. A Comparison of Sequential and Concurrent Engineering

Where changes were made, concern for *survival* in the face of increased competition, particularly from Japanese manufacturers, often provided a new incentive for companies to improve the quality of their products and increase the efficiency of their product development processes. As the pressure to improve quality and efficiency increased, new computer-based design and analysis tools gave specialists from different engineering disciplines the freedom of working with the same description of the design to evaluate the effects of particular design features. The companies that have been successful in concurrent engineering have embraced the philosophy of continuing improvement, and they are using new tools as well as traditional techniques to implement this business philosophy.

Although the study team found examples of companies that are moving in the direction of concurrent engineering, none of them claimed to have developed "the one best way". The

people affected by the changes say that progress has been difficult, that mistakes have been made, and that enthusiastic advocacy and support by top management have been essential. None of the companies said that concurrent engineering, in isolation, is capable of producing the type of improvements needed to remain competitive. Concurrent engineering is part of an integrated corporate competitiveness plan. Nevertheless, they are pleased with their accomplishments and they are actively looking for additional improvements.

3.1.1 Classification of Activities

The study team identified three complementary classes of activities among the initiatives described:

1. engineering-process initiatives such as the formation of multidisciplined teams;

2. computer-based support initiatives such as improvement of computer-based design tools, including giving the user an environment that integrates separately developed software; and

3. use of formal methods including application of special purpose tools for design and production support.

The first class of actions are initiated by management and seem to be the first elements implemented. There are cultural barriers to these initiatives, but with management support they can be overcome. Getting an integrated computer-based support environment is a difficult technical challenge. Developing a culture that takes continual advantage of observation and problem solving to create knowledge is a never-ending challenge. The three classes of initiatives are discussed in greater detail below.

Engineering process initiatives are management actions to improve the organization and the procedures used to develop a product. Leadership at the highest corporate and government levels driving continuous quality and productivity improvement is a prerequisite for successful implementation of concurrent engineering. Changes to the status quo, especially the cultural changes required for concurrent engineering, are not likely to be successful or to endure without top management leadership and support.

Early involvement of representatives of manufacturing is a minimal step in this direction. Most of the case studies show that companies form teams which include marketing, production, engineering, support, purchasing, and other specialists. Team members are selected for their ability to contribute to the design effort by early identification of potential problems and by timely initiation of actions to avoid bottlenecks. This is not equivalent to forming committees where members often delay decision making; instead design teams get faster action through early identification and solution of problems. In some cases, the effectiveness of design teams can be traced to recent advances in management disciplines and information system developments. Most of the companies visited during this study

have undertaken substantial education efforts in this area.[13] Other management initiatives include the following:

- emphasizing attention to customer needs and quality improvement,

- improving horizontal integration of the organization,

- promoting employee involvement in generating new ideas for improvement,

- requiring engineering comparisons of proposed products and competitive offerings, and

- establishing closer relationships with suppliers to include supplier involvement during conceptual design.

Computer-based support initiatives cover a range of computer-aided tools, database systems, special purpose computer systems that improve design verification, and computer-based support of product design, production planning, and production. The companies differ in the sophistication of their systems, but those companies making advances in this area share a goal of using a single data object as a source for many engineering functions including design synthesis and verification as well as planning production processes. This use of a shared, common data object by specialists throughout an enterprise provides a mechanism for concurrently performing the product and process design tasks.

A solid model[14] of the object being designed is frequently used as the single data object that allows automated systems to be integrated. In many cases, several companies comprising a development team are sharing access to the same solid model. Among companies doing electronic design, simulation is a critical tool. Mechanical design, tooling, machining, and assembly need accurate solid models. Feature-based design and group technology are approaches to creating order and imposing regularity on the design process.

Aircraft companies use finite element models (FEM) and computational fluid dynamics (CFD) to support design. In attempting to provide rule-based design systems, several companies[15] are developing practical applications of expert systems.

Formal methods[16] are difficult to categorize. This class includes process control techniques that date to the 1930s, such as statistical process control (SPC),[17] design of

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13. Boeing, Deere, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments. Sources of education include local colleges and universities, special purpose institutes, consultants, and in-house education programs.

14. Robert Wolfe et. al. "Solid Modeling for Production Design," *IBM Journal of R&D* (May 1987). Describes use of solid modeling for both mechanical and semiconductor design and evaluation. The systems described are GDP for mechanical applications and OYSTER for semiconductor applications.

15. Litton Amecom, McDonnell Douglas Astronautics, Deere, IBM, AT&T, Texas Instrument, ITT, Northrop, and Hughes all mentioned some initiative in expert system or rule-based design.

16. See Appendix B for further discussion of the formal methods.

17. Statistical process control is sometimes thought of as applying to manufacturing processes and not to design or service activities. There is abundant evidence that SPC provides direct benefits for improving a wide range of processes, including design and that it also provides indirect benefits to the design process when it is used in manufacturing. The indirect benefits result from feedback of more reliable information about manufacturing process capabilities and limitations. This information is used to design

experiments, newer tools (such as design-for-assembly developed by Boothroyd Dewhurst Inc.), and a range of quality engineering techniques for managing complex system trade-offs and for finding optimum design and production process parameters. These include statistical tools for data analysis such as design-of-experiment, robust engineering principles as proposed by Taguchi, quality function deployment (QFD), and the techniques used by Pugh.[18] Other methods that have been useful in problem solving include Ishikawa's seven tools,[19] response surface methods, group technology, exploratory data analysis, and fault-tree analysis.[20] These methods are used for different purposes, but they are all designed to help people understand the behavior of processes, products, mechanisms, and so forth, which otherwise could not be understood as thoroughly. If used properly, the methods and tools are a tremendous aid in design, production, and engineering, yielding sharply reduced life cycle costs, shortened design cycles, and improved quality.

The apparent diversity of the formal methods sometimes masks the more important process that takes place when they are used properly. This underlying process is the scientific approach to problem solving. For a company to be successful using the approach, its employees must develop the habit of identifying problems and solving them so as to improve the company's processes. Once problems are identified and analyzed, the choice of a particular formal method will depend on the situation. Appendix B contains a more detailed description of the formal methods, but the following paragraphs are provided for brief introduction.

An SPC standard was developed for the War Department in December 1940 by the American Standards Association. It is a technique for using statistical sampling methods to determine the regularity of a process. The original standard was revised and the use of SPC is described in ANSI Z1.1-1985, Z1.2-1985, & Z1.3-1985. A brief description of SPC is included in Appendix B.

Design of experiments or experimental design was invented and developed in England in the 1920s by Fisher. It has been used in agriculture, medicine, and biology. In manufacturing, design of experiments provides tools for designing and conducting experiments in an efficient way so that optimum values for product and process parameters can be identified. Deere and Company reported using traditional methods for design of experiments.

Design-for-assembly software is commercially available to help designers evaluate the benefits of using fewer parts, better fasteners, and more efficient assembly techniques. One

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products with characteristics that match a company's ability to produce them.

18. Pugh, S., "Concept Selection—A Method that Works," *Proceedings I.C.E.D.*, Rome (March 1981), WDK 5 Paper M3/16, pp 497-506.

19. The tools are: histograms, cause-and-effect diagrams, check sheets, Pareto diagrams, graphs, control charts, and scatter diagrams. Kaoru Ishikawa, *Guide to Quality Control*, Asian Productivity Organization, Tokyo, 1982.

20. A more complete listing can be found in Appendix B.

product was developed by Boothroyd Dewhurst, Inc.[21] and has been licensed by approximately 300 companies in the United States and Europe. Many dramatic product improvements have been reported through its use, particularly in the automobile and consumer products industries. Ford Motor Company recently reported total savings in excess of $1 billion through widespread application of the Boothroyd Dewhurst software system.[22]

Pugh is a proponent of encouraging creativity during the conceptual design stage and using unbiased evaluation criteria to develop the strongest concepts.

Robust design[23] has come to be associated with Taguchi. His engineering innovations and statistical methods, however, can be addressed separately. He has introduced some new and very important quality engineering ideas. He stresses the importance of closeness-to-target rather than within-specification objectives. He recommends using statistical design to formulate a product or process that operates on target with smallest variance, is insensitive to environmental disturbances and manufacturing variances, and has the lowest possible cost.[24]

Robust design is achieved through system design, parameter design, and tolerance design. System design is a search for the best available technology, parameter design selects optimum levels for design parameters, and tolerance design establishes the manufacturing tolerances.[25] Parameter design and tolerance design make use of planned experiments. Although there is general agreement that the principles of robust engineering are an important contribution, the question of the selection of statistical methods for conducting the experiments and analyzing the results remains open within the scientific community.[26] The terms "Taguchi Experiments", "Taguchi Methods", and "Design of Experiments" are

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21. *Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield (1985).

22. Peter Dewhurst, unpublished correspondence (September 20, 1988).

23. The terms robust design, robust engineering, and robust product design refer to an engineering philosophy that seeks to reduce variability of some important characteristic of a product in the presence of variability in the manufacturing and use environments. It does not, unless specifically noted, refer to the robustness of an experimental design or of the inferences that can be drawn from an experiment.

24. George E. P. Box, Discussion Section, *Journal of Quality Technology*, Vol 17, No. 4, (October 1985) p. 189.

25. Genichi Taguchi, *Introduction to Quality Engineering*, Asian Productivity Organization, Dearborn, MI, 1987

26. For an example of such discussions see: Raghu N. Kacker, "Off-Line Quality Control, Parameter Design and the Taguchi Method," *Journal of Quality Technology*, Vol. 17, No. 4, (October 1985), pp. 176-209; Myron Tribus and Geza Szonyi, "The Taguchi Methodology: An Alternative View," (December 1987); Ramon V. Leon, Anne C. Shoemaker, and Raghu N. Kacker, "Performance Measures Independent of Adjustment: An Explanation and Extension of Taguchi's Signal-to-Noise Ratios," *Technometrics*, Vol. 29, No. 3, (August 1987), pp. 253-285; George Box, "Signal-to-Noise Ratios, Performance Criteria, and Transformations," *Technometrics*, Vol. 30, No. 1 (February 1988), pp. 1-40; Ikuro Kusaba, "Statistical Methods in Japanese Quality Control," *Societas Qualitatis*, Vol 2, No. 2, (May/June 1988), Union of Japanese Scientists and Engineers; and Genichi Taguchi and Madhav Phadke, "Quality Engineering Through Design Optimization," *Conference Record*, IEEE Globecom 1984 Conference, Atlanta, Georgia, IEEE, pp. 1106-1113.

sometimes used interchangeably by practitioners. This report uses the terms that are applied by the person who performed the experiment.

Participants in the concurrent engineering workshops were clearly opposed to any initiative that imposes some rigid guideline for using one or more of the formal methods. They believe that each company should be free to decide which techniques are most useful in a particular situation. Moreover, one group of participants concluded that individual formal methods could be used independently of other methods.

Reported use of the methods varied considerably. Only three of the companies studied (AT&T, Aerojet Ordnance, and ITT) reported making extensive use of of robust engineering and Quality Function Deployment (QFD). Boeing described an initiative to restructure their systems engineering process to perform many functions included in QFD. IBM described a top-down design method that sounded very similar to QFD.

This initial study does not include a survey of which methods are most widely used in the United States. A recent article from Japan[27] describes the statistical methods mentioned in the presentation to the annual quality circle conference. The most widely used methods were the Ishikawa tools, design of experiment, and tree analysis (QFD). Table 2 lists the frequency of use of various methods at the 1987 Japanese quality circles conference.

27. Ikuro Kusaba, "Statistical Methods in Japanese Quality Control," *Societas Qualitátis*, Vol 2, No. 2, (May/June 1988), Union of Japanese Scientists and Engineers.

TABLE 2. Use of Formal Methods

Frequency	Method
78	graph
43	design of experiment
40	Pareto chart
40	tree analysis & QFD
39	cause & effect diagram
36	histogram
22	scatter diagram
18	FTA
18	correlation & regression
13	control chart
10	ANOVA
10	computer techniques
9	statistical test & estimation
9	others
8	multiple regression
6	relation chart
4	FMEA
3	process capability
3	Weibull distribution
3	simulation
2	principal component analysis
2	discriminant & cluster analysis
2	quantification theory
1	time series

Table 3 shows the extent to which the case studies[28] identified the use of one or more of these approaches. The meanings for the table entries are given below:

Approach	Key	Definition
Engineering Process Initiative Computer-based Support	G	Approach was used.
	-	Approach not used.
Formal Methods	S	Statistical process control
	D	Design of experiments
	T	Taguchi methods
	A	Design for assembly
	Q	Quality function deployment

TABLE 3. Concurrent Engineering Themes

Approaches to Concurrent Engineering			
Case Study	Engineering Process Initiatives	Computer Based Support	Formal Methods
Aerojet Ordnance	G	G	STQ
AT&T	G	G	SDT
Boeing	G	G	-
Deere	G	G	SD
IBM	G	G	ASQ[30]
Hewlett-Packard	G	G	SDAQT
ITT	G	G	STQ
McDonnell Douglas	G	G	ST
Texas Instruments	G	G	AST

28. See Appendix A for the complete case studies.

3.1.2 Characteristics of Companies

Several common characteristics have been found in the companies that successfully deployed concurrent engineering:

1. Upper management supported the initial change and continued to support its implementation.

2. Changes were usually substitutions for previous practices, not just additional procedures.

3. The members of the organization perceived a need to change. Usually there was a crisis to be overcome. Often the motivation seemed to center around retaining or regaining market share.

4. Companies formed teams for product development. Teams included representatives with different expertise, such as design, manufacturing, quality assurance, purchasing, marketing, field service, and computer-aided design support.

5. Changes included relaxing policies that inhibited design changes and providing greater authority and responsibility to members of design teams. Companies practicing concurrent engineering have become more flexible in product design, in manufacturing, and in support.

6. Companies either started or continued an in-place program of education for employees at all levels.

7. Employees developed an attitude of ownership toward the processes in which they were involved.

8. Companies used pilot projects to identify problems that were associated with implementing new concurrent engineering techniques and to demonstrate their benefits.

9. Companies made a commitment to continued improvement. None of the companies said it was prepared to freeze the latest process as the ultimate solution to design and production.

In addition to the common characteristics, different approaches were used to actually deploy concurrent engineering in the organization, in the product realization process (development through production and support), and in the rate of deployment. These differences are discussed briefly in the following paragraphs.

3.1.2.1 Organizational Deployment Differences

None of the companies studied implemented new concurrent engineering techniques simultaneously throughout the entire organization. Each company deployed new techniques

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30. IBM uses CUSUM and EWMA in addition to Shewhart charts, and their comprehensive, top-down system design method is similar to QFD.

by stages. Some companies taught key people in different parts of the organization how to use the new methods. These key people were then expected to demonstrate the benefits of the techniques in their immediate environment, thus winning wider acceptance of change. Another approach to deployment focused on changing a smaller group, usually for some pilot project. A smaller group received education in the new techniques, established new methods of work, and applied the new approach on an actual project. The smaller group acted as a role model for further deployment of concurrent engineering. Both methods have worked well. The largest single group reported to have implemented new methods as a group was approximately 400 people.

3.1.2.2 Introduction Point Differences

Once a decision had been made to pursue concurrent engineering, most companies introduced it at one end of the product realization process and then expanded its use either upstream or downstream. Several companies revised their use of SPC on the production floor and then introduced more new techniques as they moved upstream in the design process. Others concentrated on introducing concurrency in the product development by starting in the design process. There was agreement that improvements in design have greater payoff over the life-cycle than improvements in production, but production improvements yield an immediate return. In either case, successful companies tend to disperse improvements throughout the process of designing, producing, and supporting a product.

3.1.2.3 Rate of Change Differences

Companies differed in the rate at which they implemented change. Typically, companies that were experiencing the most serious crisis were willing to implement change at a faster rate. Successful companies implemented gradual changes as part of their long-standing improvement process.

3.1.3 Misconceptions

There are misconceptions about concurrent engineering. To help overcome them, it is helpful to describe what concurrent engineering *is not*.

First, concurrent engineering is *not* a magic formula for success. The best system cannot compensate for a lack of talent. The companies studied have hired and trained engineers who are able to identify important design parameters, and who are capable of creating solutions to problems. At least one of the companies said that a significant part of their success was the fact that people worked harder. Concurrent engineering is an approach for improving the efficiency of good people who work hard; it provides no guarantees of success.

Next, concurrent engineering is *not* the arbitrary elimination of a phase of the existing, sequential, feed-forward engineering process. For example, it is not the simple, but artificial, elimination of a test-and-fix phase or of full-scale engineering development. Concurrent engineering does not eliminate any engineering function. In concurrent engineering, all downstream processes are co-designed toward a more all-encompassing, cost-effective optimum design.

Next, concurrent engineering is *not* simultaneous or overlapped design and production. Concurrent engineering entails the simultaneous design of the product and of the downstream processes. It does not entail the simultaneous design of the product and the *execution* of the production process, that is, beginning high rate production of an item that has not completed its test, evaluation, and fix phase. That approach is very risky. On the contrary, concurrent engineering emphasizes completion of all design efforts prior to production initiation.

On a somewhat less dramatic, but equally important note, concurrent engineering is not just design for producibility, or design for reliability, or for maintainability. Concurrent engineering includes all of these with the added requirement that the objective is for the design optimization to integrate these domains within a cost-effective engineering process.

Also, concurrent engineering is not the same as conservative design. Conservative design seeks robustness[31] by using derated parts, redundancy, extremely close tolerances, etc. Thus, both conservative design and concurrent engineering may entail robustness but by different approaches. In conservative design, higher cost parts, that is, those that are better than apparently required or those that are built to a very high tolerance, are routinely used to achieve high quality. In concurrent engineering, robustness is sought by attempting to optimize over a larger set of processes and by determining how to achieve the resulting target values with the lowest cost parts. The evidence found in this study shows that concurrent engineering does not necessarily lead to more conservative design. Instead, concurrent engineering leads to products being tolerant of use and manufacturing variation and at less cost than sequential design.

Concurrent engineering also does not imply conservatism with respect to the incorporation of new technologies in the product.

Finally, concurrent engineering does not require conservative testing strategy, a completely different approach to high quality. Here, conservative testing means a strategy in which robustness is achieved by *planned, repeated* test-and-fix cycles (refining the design through testing). Concurrent engineering tries to approach one-pass designs in place of repeated test-and-fix cycles.

Because concurrent engineering is dependent on a total quality management philosophy, skeptics sometimes confuse it (concurrent engineering) with a misapplication of quality improvement, conservative inspection. Concurrent engineering does not imply conservative inspection strategies. Instead, it seeks to achieve manufacturing repeatability through product robustness and by designing a manufacturing process that includes the means for monitoring and controlling itself (either manually or automatically). There was widespread acceptance among the workshop participants of the axiom that inspection alone does not improve quality, does not avoid problems, and does not improve profits. Conservative inspection strategies are necessary only in a few application domains[32] and these can be

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31. Informally, robustness is the extent to which an object or class of objects exhibits high quality in the presence of manufacturing differences or environmental noise and wear.

32. For example, in some applications, such as communication satellites, the extremely high cost associated with failure during product use justifies 100 percent inspection during production.

identified early in advanced design. In the typical situation, concurrent engineering techniques seek to eliminate the need for conservative inspection. Test-and-fix cycles can be viewed as the conservative inspection strategy for engineering.

3.2 Benefits

Several companies presented evidence of how their application of one or more of the elements associated with concurrent engineering helped them to achieve the goals of lower cost, higher quality, and shorter development times. Although the stories sometimes represented only one part of concurrent engineering, they give an indication of what can be achieved. Application of concurrent engineering methods, as described in the case studies, achieved precisely the categories of benefits that are needed in the acquisition process: lower cost, shorter development cycles, and improved quality. For example, IBM Poughkeepsie Development Laboratory used a team approach called the "Total Concept Facility" (TCF) for large computer system mechanical/power/thermal design. They did not use the term concurrent engineering, but their approach is an excellent example of concurrent engineering. They attribute improvements as shown in Table 4 (normalized) to 3-D design and analysis tools as well as to the TCF. They did not separate the contribution of the different elements to their overall success.

TABLE 4. IBM Poughkeepsie Development Laboratory Large Systems Mechanical/Power/Thermal Design

	Traditional Approach	Total Concept Facility Improvement	Future Projection
Unique Part Numbers	1.0	.50	.29
Engineering Changes	1.0	.41	.18
Assembly Hours	1.0	.55	TBD

The next three subsections present reported[33] benefits by category: quality, cost, and schedule.

3.2.1 Reported Quality Improvements

Several of the companies visited during the study reported that their decision to use concurrent engineering procedures can be traced to corporate quality improvement

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33. The data presented by the companies were accepted at face value.

programs. When these companies pursued a vigorous quality program to improve their competitive capabilities, they often found that concurrent engineering was a natural part of such a program. U.S. companies are accepting the view of quality that the Japanese learned from Sarasohn, Deming, and Juran. Corporations are sending senior executives to U.S. quality seminars and courses. They are learning that improving quality does not have to drive prices up, but if quality is improved through attention to the system (or process) then costs go down. The cost savings result from reductions in scrap and rework (the elimination of the so-called "hidden factory"), reduced warranty costs, elimination of inspections, and the resulting improvement in production efficiency. The view of quality as a driver for competitiveness improvements is gaining wider acceptance.

3.2.1.1 Quality and Robustness

For the purposes of this report, the *quality of some subject* (i.e., or some product or process) means the extent to which the subject satisfies the expectations and needs of its users in operational environments over a period of time.[34] A subject may have higher or lower quality. Higher quality may occur by either closer satisfaction of the users' needs and expectations during a given period or by satisfaction at a certain level over a longer period. This means that specific measures of quality must be defined if one wants to compare the quality of one subject against that of another. Such a measure must account consistently for the actual user expectations for the subject, the operational environment, and the duration of operation.[35]

This definition of quality may be extended to a class of subjects, for example, the collection of F/A-18 fighter aircraft produced to date. Measures of quality may be easier to apply to a class of subjects than to an individual subject because of the applicability of statistical techniques. In either case, quality of a subject or of a class, the precision of the idea of quality depends on the precision of the ideas of "expectation", "needs", "environment", and "duration of use". That is, if one does not know how an object is to be used or over what period of time, one cannot know its quality (by our definition).

Given this definition of "quality", there is a closely related term in use in the quality engineering community: *robustness*. For the purposes of this report, robustness is the extent to which an item or class of items exhibits high quality in the presence of manufacturing noise or environmental noise and wear. The relationship between the notions of quality and robustness as used in the quality engineering community seems to be more a matter of specificity than of important substance. Given a requirement and intended useful life, robustness can be used as a measure of product quality. Sometimes robustness (hence,

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34. A weapons system is designed for use in a combat environment, but may be used for long periods in a peacetime environment. Both environments are included in the category "operational". Naturally, satisfactory operation in the former is more critical.

35. This is only one of several possible definitions of quality, but is the most appropriate for the purposes of this study. For a further discussion of the different definitions of quality, see chapter 3 of David A. Garvin, *Managing Quality*, The Free Press, New York (1988).

quality) is captured as the reduction of performance variation about a target value in the presence of variations in the operational environment and over the duration of use. Thus, if a rifle fires when the trigger is pulled (the target value) in hot, medium, and cold weather, when clean or covered with mud, sand, or ice (environmental noise) over many years following a reasonable maintenance schedule (intended duration of use), it is robust with respect to firing. This robustness is an exhibit, or possibly measure, of the high quality of the rifle.

Companies visited usually associate *quality* of their design with fewer engineering changes after the product being designed enters high volume production and use. They use reduction of scrap and rework as a measure of the quality of their production processes. Some companies that have adopted more strenuous efforts to reduce their process variability use other measures of quality such as Taguchi's loss function.[36]

3.2.1.2 Reported Quality Improvements—Examples

Examples of reported quality improvements are listed below:

- Aerojet Ordnance salvaged 400,000 pyrotechnic pellets that would have been discarded because of insufficient burn times. The pellets could be used because Aerojet redesigned the loading parameters on the basis of Taguchi experiments. They improved the consistency of tracer rounds as measured by μ/σ (mean/standard deviation) by a factor of 5. Their support on the ADAM program identified correct design parameter settings so that yield was improved from approximately 20 percent to 100 percent, a 400 percent improvement.

- AT&T achieved a fourfold reduction in variability in a polysilicon deposition process for very large scale integrated (VLSI) circuits (1.75 micron design rules) and achieved nearly two orders of magnitude reduction in surface defects by using Taguchi methods.

- AT&T reduced defects in the 5ESS™ programmed digital switch up to 87 percent through a coordinated quality improvement program that included product and process redesign.

- Boeing reduced engineering changes per drawing from 15 to 1 through improved teamwork and use of computer-based support. Their inspection-to-production hour ratio improved from 1:15 to 1:50 because of improved teamwork and use of process control methods.

- Deere reduced the number of inspectors by two thirds by emphasizing process control and by linking design and manufacturing processes.

- ITT performed over 3000 Taguchi experiments in the past 3 years. Most (90 percent) involved no company capital investment. A few of the savings that resulted from using robust designs and robust manufacturing processes include $500,000 by reducing rejects, $125,000 savings on tool costs, $1,100,000 savings on a solder process, 28 percent improvement on a power supply product losses, and $97,000 annual savings in a

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36. See Appendix B for a discussion of formal methods.

traveling-wave tube process.

- McDonnell Douglas reduced rework costs 29 percent, scrap costs 58 percent, and non-conformances by 38 percent through a corporate renewal effort that incorporated improved teamwork, better computer support, and renewed emphasis on process controls. They reduced defects per unit in a weld process by 70 percent.

- Hewlett-Packard reduced its company-wide field failure rate for all products 83 percent over the past 7 years. Scrap and rework have been reduced by as much as 95 percent in some operations. Thousands of factorials, fractional factorials, central composite, and response surface experiments have been conducted over the past few years. Very few of these experiments (less than 7 percent) have required any capital investment. Results of these experiments have led to millions of dollars in savings. A few examples include $1,000,000 in one year warranty savings for one product, $260,000 per year savings in a gold-plating process, 88 percent decrease in labor and material cost in another chemical plating operation, $650,000 savings on a solder machine, 75 percent error reduction in an automatic component insertion process, and 35 percent reduction in process development time for a product.

A more complete description of the actions taken and results achieved is found in Appendix A.

3.2.2 Reported Cost Reductions

Reports of cost reduction include the following classes of cost savings:

- Reduced bid in company proposals.[37]

- Reduced costs in the design phase.[38]

- Reduced costs during fabrication, manufacture, and assembly.[39]

- Costs reduced by parts reduction and inventory control.[40]

- Costs reduced by reducing scrap and rework.[41]

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37. McDonnell Douglas had a 60 percent reduction in life-cycle cost and 40 percent reduction in production cost on a short range missile proposal. Boeing reduced bid on mobile missile launcher and is realizing costs 30 to 40 percent below bid.

38. AT&T and IBM reduced the number of passes and made extensive use of computer-aided design verification during design saving money and time. Deere reduced product development cost 30 percent.

39. Boeing reduced labor rates by $28 per hour. IBM reduced direct labor costs in system assembly by 50 percent. ITT saved 25 percent in ferrite core bonding production costs. Allied Signal saved more than $3,000,000 annually in a bulk chemical process as a result of experimental design.

40. Boeing reduced parts lead time by 30 percent. AT&T reduced parts by 1/3 on SMT packs and reduced costs to 1/9. AT&T Denver Works decreased in-process inventory 64 percent. Deere reduced the number of parts to fabricated and stocked by 60 to 70 percent. Hewlett-Packard Instruments Division recognized inventory reductions of 62 percent and a productivity increase of 250 percent.

41. Deere reduced scrap and rework costs by 60 percent. Using a Taguchi experiment, ITT saved $400,000 by reducing rejects on one product. Aerojet Ordnance salvaged an entire lot of pyrotechnic pellets through use of a Taguchi experiment. ITT saved $1,100,000 annually by improving a soldering process based on a Taguchi experiment.

3.2.3 Reported Decreases in Development Cycles

There were many reports of shortened development cycles. The reports are so impressive that a reader is cautioned to avoid expecting that concurrent engineering methods will eliminate all the bottlenecks and long lead-time items in a weapons system development. Nevertheless, the reported savings indicate substantial improvements were achieved. Samples are listed below:

- AT&T reduced the total process time for the 5ESS™ Programmed Digital Switch by 46 percent in 3 years.

- Boeing's Ballistic Systems Division reduced parts and materials lead times 30 percent. One part of design analysis reduced from 2 weeks (with three to four engineers) to 4 minutes (with one engineer).

- Deere and Company reduced product development time for construction equipment by 60 percent.

- ITT reduced the design cycle for an electronic countermeasures system by 33 percent, and its transition-to-production time by 22 percent. Time to produce a certain cable harness was reduced by 10 percent.

- McDonnell Douglas cut 18 months from one step of a fighter aircraft development. They are now able to perform a preliminary concept redesign for a high-speed vehicle in 8 hours instead of 45 weeks. They reduced cycle time 20-25 percent by using Computer-aided Acquisition Logistics Support (CALS) digital data instead of paper methods.

3.2.4 Interactions

Although the approaches to concurrent engineering exhibit the three themes described above, there are strong interactions among them. Some of these interactions are discussed below.

- *Multifunction teams.* The proximity and interaction of personnel from the different disciplines have a major positive effect by itself. Assignment of decision responsibility to the team allows big improvement in problem resolution which improves product and process development times.

- *Systems engineering.* Analysis of design features and their relation to observed reliability and producibility is a prerequisite to cross training personnel so that they achieve a systems perspective. The analyses and training are essential to quantitative predictions of producibility and reliability. Computer support has proven useful in performing these analyses without delaying the design process.

- *Computer support.* A parts database is valuable in conceptual design in terms of evaluating options. Product definition and shared common product design databases are enabling forces for a variety of concurrent engineering functions. Feasibility analysis, simulations, integration management, design release, and transfer to automated production processes all support decision making throughout the engineering process.

- *Complexity management.* The level of program integration and complexity affects the leverage of concurrent engineering methods and techniques. For complex systems, systems integration must address both management and design systems. Product and process simulations are important at the systems level. At the component level, process and product optimization to achieve robust design may be of more immediate value.

- *Integration.* At the component level, concurrent engineering can be implemented by integrating the design system with a flexible manufacturing cell. Given that the design and manufacturing systems employ features with known variability, cost, performance, and quality objectives are met.

3.3 Pitfalls

The benefits cited in this report are encouraging, but they have not been achieved easily. One of the companies encountered in this study related some of the mistakes and lessons learned in their implementation of concurrent engineering.

> Top management commitment in the form of learning, understanding, and leading the concurrent engineering efforts with a communicated, unwavering purpose and management involvement is absolutely vital to long-term success. The many improvements and cost savings we have recognized thanks to concurrent engineering are due mostly to the application of the powerful statistical and quality improvement techniques at the small, local level (for example, a particular machine or manufacturing process). Granted, these have been very important and worthwhile. But the really impressive savings (hundreds of millions of dollars) remain largely unrecognized because they result only from improvements of the larger "systems" over which only top management has control. These larger systems include policies of the company; training that people receive; actions of management; policies for purchasing parts; barriers between departments, between divisions, etc.; emphasis on short-term thinking and profits; policies for never-ending improvement; the way employees are evaluated; fostering of teamwork; and so forth. To date, most top managers have failed to comprehend, or at least execute, their critical responsibility. Their verbal "support" is simply not sufficient. *The concurrent engineering effort must be led.* Even at the small, local levels, the successful efforts have been led by the are discussed respective low-level or middle mangers. To quote Myron Tribus, part of management's responsibility is to work *on* the system that the people underneath have to work *within*.

> Our corporation's lack of leadership for concurrent engineering has resulted in an effort without any clear direction or guidance both within many divisions and between the divisions. This fosters the widespread perception that concurrent engineering is a fad that will eventually go away. In contrast, the efforts underway at Ford Motor Co., Florida Power

& Light, and a few other companies are well-directed and guided because of top management leadership, starting with the Chairman of the Board.

Most divisions placed too much emphasis on the techniques of concurrent engineering (SPC, QFD, Design of Experiments, etc.) and not enough emphasis on the critical management philosophy underlying the application of the techniques. This partly explains the lack of top management understanding and involvement. Top management views concurrent engineering as something the lower levels learn and apply. Concurrent engineering is more a philosophy of management than a bag of techniques. Granted, the techniques are crucial to the execution of the philosophy, but without the guiding philosophy the techniques are not as effectively used at all levels, nor are the great potential improvements fully realized. Our company has ushered through continuous "waves" of techniques over the past several years fueling the perception that concurrent engineering is a coming-and-going fad. These techniques have included SPC, Quality Control Circles, and many others. People are confused about what they ought to be doing today.

We should have focused more on the management philosophy in our initial training, then followed with the techniques. This would have "grounded" and guided the effort. Because we did not do this, many people still view concurrent engineering as a bunch of techniques they may or may not apply in their "same old way" management environment. So far, the fact that the techniques are powerful is not sufficient to ensure their successful proliferation. We missed our chance to teach top management properly the first time. "Rework" training has been only marginally successful.

Most divisions began teaching low- and middle-level managers before teaching top management. Consequently, lower-level management tried to apply the techniques with little upper management understanding and guidance. Upper management did not know how to support the efforts, what was their responsibility, what questions to ask. The end result was that many attempts sputtered along then stopped, leaving a bad taste with people. If we were to start completely over again, we believe the best approach would be to have top management take whatever time was necessary (a good year probably) to learn and understand the principles, philosophy, and some simple tools of concurrent engineering; understand their responsibility; develop their purpose, direction, and plan for implementing the effort companywide (pilot efforts); and then execute the plan with appropriate leadership.

We have found that massive "generic" training of employees at all levels on SPC techniques is far less effective than similar training tailored and

taught to specific small groups (10-15 people). When we train a specific group, we require the manager and supervisor of the group to be present and actually do some of the training.

Similar opinions were voiced by many participants and they led the study group to include a specific recommendation urging that senior OSD executives avoid the the same mistakes.

A second pitfall was described by members of one division of a larger company. This division had a contract with a Service program office that was acting in the role of system integrator. The contract requires the engineering and manufacturing branches of the company to maintain separate relationships with the program office. For example, when the engineering branch is funded to design improvements or modifications for the weapon system, the output of this activity is an engineering change proposal (ECP) that constitutes a full technical change of the technical data package. Depending on the nature and scope of the ECP, the resulting manufacturing is accomplished by the same company or else by another vendor. Final assembly is accomplished by the manufacturing division of the first company.

This contracting method separates engineering from manufacturing and, when coupled with a fixed price production contract, has several disadvantages for concurrent engineering. First, to reduce cost, improve quality, and reduce scrap, the company is limited to production process changes. Engineering changes can only be made if significant cost reductions can be demonstrated, at which time a value engineering change proposal (VECP) is processed by the engineering branch and submitted to the program manager for approval. The result is that engineering changes in production are limited to recurring cost reduction items where the cost savings outweigh the implementation costs on a 3 year payback. Second, some engineering changes are designed by competing engineering houses, so that the production organization and processes are unknown to the designers. Thus, continuous improvement is stifled and production is decoupled from design. In this case, the program office, while intending to serve as an integrator, was actually a barrier between different divisions of the same company.

3.4 Applicability

The goal to reduce life-cycle cost (LCC) through use of concurrent engineering during the systems acquisition phase has the potential for generating large returns on DoD's and industries' concurrent engineering investment. The earlier in the acquisition cycle that concurrent engineering is introduced, the greater the potential cost savings. One of the workshop participants related an experience where the use of concurrent engineering methods of multifunction teamwork among both the government and contractors *before* contract award had a significant payoff in improved design.

As systems decisions that affect a product's design are made, costs become defined. Therefore, the earlier in a system's design definition that the user's requirements can be addressed by the product design and associated manufacturing process, the greater the possibility of producing a robust design that can be produced quickly and at the lowest cost.

A series of studies by the Westinghouse Corporation showed the percentage of a product's life cycle cost (LCC) that could be affected by decisions made at various points in the defense acquisition cycle. For example, by the time a new product's operational scenario has been defined (concept definition phase), decisions affecting 20 percent of its LCC have been made. By the time a prototype design has been developed, 75 percent of the product's LCC have been decided. And, once a product goes into production, only about 10 percent of its LCC remains to be influenced.[42]

However, concurrent engineering requires a change to the basic way some companies conduct business. For example, new product designs historically have been the property of a company's engineering department. When the design and engineering analyses are completed, the design is passed to manufacturing for tool and process design. Manufacturing impasses resulted in a request for an engineering change and the design matured through an iterative sequential process. Concurrent engineering requires that manufacturing and tooling personnel be part of the design team.[43]

Where does concurrent engineering map into the DoD acquisition cycle? Appendix D describes how concurrent engineering can be applied in the acquisition process. It shows the method that is used, in theory, when weapons systems are developed.

If one believes that listening to the "voice of the user" by a design team is part of the process to develop a product's design requirements, then concurrent engineering would affect all system procurement activities from Milestone 0 to the start of Milestone III, or from concept definition to the end of full scale development (FSD).

3.5 Related Efforts

An observer of the acquisition process can become confused by the variety of DoD and Service initiatives to improve some part of the acquisition process. An objective of the IDA concurrent engineering task force is to define a structure within which the engineering organization, management, and technology initiatives can be placed so that gaps and overlaps can be identified. A first attempt at such a structure is presented in Section 4, but a mapping of programs into the structure has not been made. A listing of some of the related programs follows.

The DoD has ten strategies for improving weapons system acquisition.[44] The

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42. From a slide presented by James Nevins at the DARPA Concurrent Engineering Workshop, Key West, Florida (December 1987).

43. Making manufacturing and tooling personnel part of the design team is not, by itself, sufficient to satisfy the criteria for concurrent engineering.

44. The strategies are 1) bolstering industrial competitiveness; 2) improving the effectiveness of the acquisition work force; 3) conducting acquisition regulatory reform; 4) developing a strategy for international technology acquisition and logistics programs; 5) influencing how DoD manages special programs; 6) emphasizing commitment to small and small disadvantaged businesses; 7) forging a new relationship between DoD and industry; 8) instituting a new acquisition technique called "could cost"; 9) reducing the lead time for the introduction of new technology; and 10) total quality management. Concurrent engineering is an implementation mechanism for total quality management.

Defense Manufacturing Board and Service manufacturing technology (MANTECH) programs are trying to improve the manufacturing capabilities of the industrial base.

3.5.1 Management Initiatives

The management initiatives include DoD and Service programs. The Computer-aided Acquisition and Logistics Support (CALS) initiative has the objectives of integration of contractor design and logistics databases, paperless delivery of technical data, and integration of support activities (e.g. reliability and maintainability) with computer-aided-engineering software. *DoD 4245.7-M, Transition from Development to Production*, strives for disciplined engineering that includes the tasks of design, test, and production. It facilitates that engineering discipline by providing "templates" to show where decisions and actions fall within the boundaries of an effective and efficient, low-risk program.[45] The Department of the Navy publishes a series of documents (for example, NAVSO P-6071) that describe the best engineering practices, including *The Transition from Development to Production.*[46] The Air Force R&M 2000 Process spans management and technical initiatives. It provides twenty-one[47] building blocks that can be tailored to individual programs to provide increased combat capability by improving the reliability and maintainability of weapons systems.

The Aeronautical Systems Division (ASD) of the USAF has several initiatives to improve the acquisition process. The *Mil-Prime System Specification* communicates to offerors the development requirements stated only in performance terms with specific values "blank". Product integrity programs for aircraft structures, engine structures, avionics and electronics systems, mechanical equipment and subsystems, and software integrity programs are organized, disciplined approaches to the design, analysis, qualification, production and life-management of aeronautical systems.

Military Standards are also concerned with improving the acquisition process. *MIL-STD-490A, Specification Practices; MIL-STD-499A, Engineering Management; MIL-STD-1388-1A, Logistic Support Analysis;* and *MIL-STD-1521B, Technical Reviews and Audits for Systems, Equipment, and Computer Software* are just four of the important standards that affect the acquisition process.

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45. *DoD 4245.7-M, Transition from Development to Production* (September 1985), Preface.

46. *NAVSO P-6071, Best Practices, How to Avoid Surprises in the World's Most Complicated Technical Process*, Department of the Navy (March 1986).

47. The building blocks are can be grouped into four classes: 1) motivation [source selection, performance-based progress, and incentives and warranties]; 2) requirements [clear requirements, technician transparency, simplification, mo   rity, R&M plans, and company policy and practices]; 3) design and growth [systems engineering p   ss, allocation and prediction, analysis, growth management, parts selection, derating, computer-aided tools, and test analyze and fix]; and 4) preservation [variability reduction, environmental stress screening, system testing, and feedback].

3.5.2 Technology Initiatives

Leading the technology initiatives, the Defense Advanced Research Projects Agency (DARPA) sponsored a workshop on concurrent design in December, 1987, and is sponsoring an initiative in concurrent engineering to meet the challenge of refurbishing U.S. product competitiveness.

The purpose of the 3 day workshop was to explore the concept of concurrent engineering and how it can be used to strengthen the United States defense and commercial industrial base. The numerous presentations by participants from industry, government, and academia addressed concurrent design techniques, industrial experience, and research issues and priorities. Following the presentations, the participants convened into working groups to identify research areas that should receive attention in a prospective DARPA program.

Some of the specific recommendations by the presenters and working groups included:

- Establish a design including a unified representation capability for requirements, materials, processes, features, reliability, serviceability, scheduling, costs, capital resources, ambient conditions, etc.;

- Develop design decision aids including the capability for modeling processes, solids, assembly, costs, schedules, production, organizational impact, etc.;

- Develop computer-based design tools and tool environments (i.e., tools aware of tools) to support concurrent engineering;

- Generate and maintain databases on materials, processes, tolerances and process versus cost, methods and costs; and

- Develop better ways to manage, store, retrieve, and transmit data.

Within the Air Force alone, there are at least three CALS projects developing computer-aided design environments. The Integrated Design Support System (IDS) project is developing and prototyping an integrated system whereby design and engineering information will be made readily available to USAF logistics and operating personnel. The Very High Speed Integrated Circuit (VHSIC) program office is using the Engineering Information System (EIS) to develop standards and a prototype environment that includes cost-effective integration of user's new and existing tools and databases; management, exchange, and error-free use of engineering information; consistent user interfaces; and implementation and enforcement of local policies. The Unified Life-Cycle Engineering (ULCE) program is developing technology for an intelligent workstation which supports concurrent engineering.

3.6 Issues

People from industry who participated in this study raised several issues about concurrent engineering. Some of the issues are listed below:

- Assuming that concurrent engineering is a good philosophy for product development, how can DoD encourage its use without imposing a particular solution? Senior DoD executives can, by including discussions of total quality management and concurrent engineering as part of their continuing dialogue with industry executives, show their interest and support for improving the development process. Beyond demonstrating an interest, a directive that states a DoD policy on concurrent engineering, without being overly restrictive, is needed. A sample is included as Appendix E.

- How can the acquisition process be simplified and changed while encouraging use of concurrent engineering? Both industry and government participants expressed a belief that creation of additional new programs or publication of more regulations without eliminating or modifying current practices is not the best way to improve the acquisition process. They expressed a strong preference for consolidation, simplification, and coordination of existing standards and regulations, including updating the "templates" to include concurrent engineering methods.

- How can the many research and development programs that are related to improving the design and production processes be coordinated? The conceptual framework described in Section 4 and in Appendix C gives a means of assessing which building blocks are needed to support concurrent engineering. This framework can be used as a vehicle for creating a research and development agenda.

- How can improved customer-supplier relationships be developed in the acquisition process? This issue remains open. The benefits of establishing closer relationships with suppliers are well known among followers of Deming and practitioners of just-in-time manufacturing. At the same time, the benefits of competition cannot be overlooked and support for competitive policies is very strong in the Congress. There are no obvious simple answers to this issue, but continued analyses is called for.

- How can the DoD acquisition organization be improved to support concurrent engineering? There have been periodic studies of the weapons system acquisition process including the Blue Ribbon Commission cited earlier. Their recommendations for streamlining the management of the acquisition process are being implemented and these changes will aid the practice of concurrent engineering. Beyond these streamlining initiatives, workshop participants expressed an opinion that steps to implement multifunction teams within the various program offices, including allowing the team members to speak for their functional areas, will encourage contractors to form and use similar teams.

- Are new skills needed for DoD personnel to manage acquisition programs? The discussion of pitfalls makes it clear that new skills are needed in both the government and industry beginning at the highest levels. These skills include an awareness of the paramount importance of quality, the presence of variation, the importance of thinking in terms of the process, and an array of problem-solving tools. The recommendations section includes further discussion of the need for education and training to supply the needed skills.

- How can DoD managers evaluate a company's claims about concurrent engineering without imposing a solution? Workshop participants from the defense industrial base expressed concern about their company's continued ability to compete for DoD contracts. They are ready to make the changes that they believe are needed to become more competitive, but they do not want to start an internal improvement program, only to find that DoD will later impose some slightly different program. Neither did they want to implement some improvement whose benefits will be discounted by proposal evaluators. The recommendations section addresses these concerns by focusing on the need to evaluate a company's ability to improve its processes.

4. A CONCEPTUAL FRAMEWORK FOR FURTHER EVOLUTION

4.1 The Role of Technology in Evolving Concurrent Engineering

There are already many valuable organizational, cultural, management, and technical methods and support technologies that can be used to carry out concurrent engineering. Effective deployment of these will result in a substantially more efficient and effective weapons system acquisition process.

Current industrial experience indicates that cultural and management change is harder to deploy than technical change. If the difficult task of effecting the underlying cultural and management changes succeeds, technological improvements promise to increase dramatically the effectiveness of engineers faced with the complexity of integrating the design of weapons systems and their associated downstream processes. On the other hand, if the cultural and management changes for concurrent engineering are not implemented, it is unlikely that any highly effective technological solution will emerge.

There are opportunities for significant improvements in the technological support for concurrent engineering. Some of these improvements can be based on the application of understood technologies to the concurrent engineering process. Others require varying amounts of research or exploratory development.

A conceptual framework has been created to aid in the understanding of and programmatic planning for the evolution of the technical aspects of concurrent engineering. It provides a structure within which researchers, developers, sponsors and practitioners can discuss the issues, barriers, and opportunities of concurrent engineering. The framework provides a "how" and "why" relational structure that can be used to demonstrate how specific technological projects flow from the goals of quality improvement, cost reduction, and schedule reduction. Section 6 contains a technology recommendation geared to this with the intent that the framework be used for organizing a coherent technical program in support of concurrent engineering. The conceptual framework is detailed in Appendix C.

The four components of the framework (Figure 2) are (1) DoD Objectives, (2) Critical Functions, (3) Required Capabilities, and (4) Technical Building Blocks. Each component describes how concurrent engineering addresses the requirements described within the component with the next lower number. Turning this around, each component describes why the next higher numbered component is required. Figure 3 adds detail specific to concurrent engineering, but note that the Components 1-3 are each intended to be taken as a whole. Component 4 is intended to be taken as a whole at the level of detail shown in Figure 3, that is, areas of building blocks.

4.2 DoD Design Objectives

Component 1 consists of DoD's design objectives: to acquire the product which has the highest quality, at the lowest cost, within the shortest time. Quality, as defined earlier in the report, incorporates elements of both product performance and reliability. The cost

WHY?◄————————— —————————►HOW?

DoD Design Objectives	Critical Functions	Required Capabilities	Technical Building Blocks
1	2	3	4

COMPONENTS
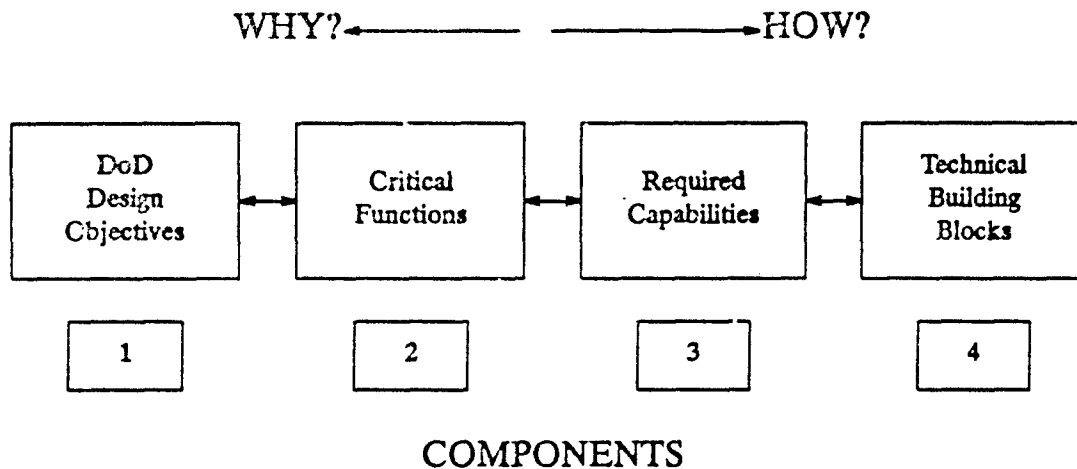
Figure 2. Framework Structure

here includes both design and production cost as well as all other costs during the product life cycle. The time relates to both the *time to availability* for a new weapons system and the *time for delivery* in response to demand for current systems. While these are the objectives of any design process, the concurrent engineering process offers unique opportunities to achieve designs that are: responsive to real user needs, provide explicit and objective trade-offs between conflicting objectives, and provide for continuous improvement.

4.3 Critical Functions

To achieve the Component 1 objectives, it is necessary to function in new ways with regard to the timing, process, and philosophy of engineering. Component 2 describes these functions. With regard to the *timing*, there must be an early understanding of the needs of all customers (buyers and users) and the requirements of all phases of the life cycle. This is accomplished by having an open and active dialogue between customer and vendor. This dialogue would, over time, transform a fairly vague set of requirements into the best specific set of time/cost/performance values available at the time. Along with the evolution of the understanding of requirements, there must be an evolution of a verification procedure that will check the eventual product against the requirements.

The *process* must change to ensure an effective and timely contribution of all responsible participants in the design/manufacture/use cycle and the objective identification and evaluation of trade-offs. The design process must allow, encourage and, in fact, assure that

- all requirements of the life cycle are considered and evaluated,

- the cross-impact of various functional decisions are understood and evaluated (with appropriate trade-off analysis),

- critical risks of various design options are identified and addressed early in the process, and

- those responsible for the various functional areas within the development and manufacturing enterprise participate with appropriate levels of responsibility and authority.

To achieve these objectives, concurrent engineering suggests four specific functions. First, there must be an integrated and continuing participation of multifunction teams in the design of product, process and support. Second, this process of integrating multiple engineering and management functions must provide for efficient iteration and closure of product and process designs. Third, the system must identify conflicting requirements and support their resolution through an objective choice of options based upon a quantitative or qualitative comparison of trade-offs, as appropriate. Fourth, the concurrent engineering process must incorporate an optimization of the product and process design. [Note: The optimization here should not be interpreted as any theoretical optimum of any individual design objective, such as system performance (for example, aircraft speed), but a very best possible combination of the most desirable objectives as defined by the customer.] This optimization can be based on either empirical or analytical (theoretical) knowledge (or both).

The *philosophy* of the entire enterprise must be one of continuous and aggressive improvement against current and projected product and process baselines. This, in turn, leads to a change in corporate focus from one of reaction to problems, to one of problem prevention.

There are four specific functions which contribute to this continuous improvement. First, open and continuous communication is necessary. This communication links the customer and the vendor and it also unites the many specialists involved in developing, producing, deploying, and supporting a product. Second, a complete (necessary and sufficient) and unambiguous statement of the users' requirements must be developed, including the priorities of various requirements to be applied in the case of trade-off analysis. Third, a complete and unambiguous description of the product and related processes must be provided to allow concurrent engineering to occur. Fourth, a baseline product and process evaluation must be established.

These three functional area changes, timing, process, and philosophy, are elements which characterize concurrent engineering. They are the differences between concurrent engineering and "good engineering practice", as it is executed in the U.S. today. All three elements are essential and of equal priority.

4.4 Required Capabilities

Component 3, *Required Capabilities*, describes requirements placed on the engineering, production, and support processes as a result of Component 2. These capabilities are present in most engineering and production processes, but concurrent

COMPONENT 1	COMPONENT 2	COMPONENT 3	COMPONENT 4
DoD OBJECTIVES	CRITICAL FUNCTIONS	REQUIRED CAPABILITIES	TECHNICAL BUILDING BLOCKS
	Early, complete, & continuing understanding of customer requirements and priorities.	Capture data on comparable products, processes, & support (lessons learned).	Data Processing & Data Structures
		Define and capture data for new weapon system product, process, & support. (complete and unambiguous description)	
Reduced Cost		Synthesize requirements into design of product, process, & support.	Frameworks/ Architectures
		Validate design of product, process, & support.	
	Translation of requirements concurrently and in an integrated fashion into optimal products and manufacturing and support processes.	Manage product, process, & support data.	Tools & Models
Reduced Time		Disseminate product, process, & support data.	
		Deliver product or data for manufacturing & supporting product.	
Increased Quality		Rapid Prototyping	Manufacturing Systems
		Process Robustness	
	Continuous review and improvement of product, process, & support characteristics.	Intelligent oversight for impact assessment of changes.	
		Proactive, concurrent availability of current design.	Design Processes

Figure 3 - Concurrent Engineering Framework

engineering places a unique set of requirements on them.

4.4.1 Data Definition and Capture, Design Synthesis, Trade-Off, and Validation

Early, complete, and continuous understanding of customer requirements and priorities requires ready access to knowledge and data and interconnections between sources of knowledge and data not currently available. This understanding has two principal elements:

- the capture of historical data, and

- the capture of data on new designs, tools, methods, and materials.

Here "capture" means not only the acquisition of detailed data, but intelligence (artificial or natural) that would allow ready access and review of this data by both highly skilled as well as less skilled people. Of course, in order for the data to be captured, it must exist or be discoverable. A significant required capability, therefore, is the set of mechanisms which generate the historical data necessary to concurrent engineering. An example would be mechanisms for generating feature-by-feature reliability and maintenance data on weapons systems in ways that are not used for manipulation for non-engineering purposes (for example, budgetary purposes).

Similar statements are appropriate for the definition of data on and synthesis of new designs, tools, methods, and materials. Here the intelligent use of data allows visibility into the trade-offs and allows the examination of constraints in a larger context which includes product and process issues, manufacturing as well as field support issues. This improved visibility further supports a continuous review process.

The availability of such tools would offer a more flexible procurement system, with shorter concept-to-deployment time, with greater visibility into the process for the designer, manager, and procuring agency.

4.4.2 Information Management, Dissemination, and Delivery

The management, dissemination, and delivery of product, process, and support information become somewhat more complex problems in a concurrent engineering world than in existing practice. Managing engineering information is difficult in the presence of integrated and continuing participation of multifunction teams in the design of product and processes. The requirement for flexibility to evolve the engineering, manufacturing, and support processes place an added burden on information management. This burden is increased by two factors: widely distributed teams and the size and complexity of weapons systems. Another function placing requirements on the product, process, and support information management capability is that of open and continuous communication between customer and vendor. All of this indicates a need for evolvable, tailorable, interoperable, secure, distributed, and high performance enterprise information management systems, starting with engineering and production. A discussion of the building blocks for such systems is in Component 4 under the heading *Information Frameworks*.

In particular, within the management of engineering and production information there must be intelligent oversight for impact assessment of changes and proactive availability of designs. In the ideal design process, every change should be evaluated for impact on all functions and the cost of the entire life cycle. In practice this is difficult to assure. Within concurrent engineering, change evaluation is enabled and encouraged by the continued multifunctional team approach. Even then, systems must be introduced which assure that evaluation. There are two steps to that assurance. First, there must be an intelligent oversight to assess the impact of changes. This assessment can be based on models of product performance, manufacturing process (including schedules), and cost. Second, to assure attention to changes and assessment of their impact by the relevant functional responsibilities, there should be a proactive availability of these designs to various functions.

4.4.3 Rapid Representative Prototyping

While product and process modeling provide valuable knowledge of their performance and adequacy, at some point there must be a "first unit production" which creates the first physical version of the product. However, the prototype is often not representative of the quality which will eventually be achieved in production. This often leads to delays and added expense in the iterative design process and invalid decisions based on prototype testing. One way to combat such problems is to achieve linkages between design systems and manufacturing systems which rapidly create representative prototypes. Some of the necessary capabilities include:

- feature-based design representations incorporating features which have manufacturing meaning

- easy (perhaps automated), quick transformation of design descriptions into hard and soft tooling or software

- flexible machinery and fixturing which allows an inexpensive and rapid changeover from current production to prototype production

- task level programming of manufacturing devices, including numerical control (NC) machine tools, robots and inspection systems.

These capabilities, taken as a whole, with the integration of the appropriate intelligence, information structures, and communication systems, could provide a system which automatically transforms feature-based designs into task-level manufacturing programs and rapidly delivers them to the manufacturing floor for production of tooling, fixtures, and representative prototypes.

4.4.4 Process Robustness

Robustness can be thought of as the insensitivity of the product quality to product and process *noise*. Noise is variability introduced either intentionally by design changes in product or process, or unintentionally through drift in process or external factors that cannot reasonably be controlled. Product changes may include the production of a variety of models over one line or the continual improvement of product design. Noise may include such factors as temperature, humidity, or variability of human performance

levels. In any case, it is desirable to minimize the variability of the units produced by making the process insensitive to changes.

4.5 Technical Building Blocks

Component 4, *Technical Building Blocks*, contains five areas of specific efforts required to improve the technical and methodological support for the capabilities at Component 3.

The first Component 4 area, *Data*, describes the kinds of information that needs to be brought to the design process for concurrent engineering. It also raises the requirement for a common *information architecture* so that information users (e.g., designers) and information suppliers (e.g., maintenance organizations) can have a common understanding of the meaning of the information.

The second Component 4 area, *Information Frameworks*, describes the requirement for a structure of specifications and standards for establishing, storing, executing, and evolving information-based policies and tools. An information framework also has capabilities to organize, access, and evolve the data used by the policies and tools. Using a conventional or standardized framework that has been designed for evolvability and tailorability allows for easier interaction among tools, among engineers, among teams, and among organizations. DoD has several information framework efforts underway. These include systems driven by the needs of airframe specialists, electronics specialists, logisticians, and software engineers. It is important that DoD integrate the vision of these efforts.

The third Component 4 area, *Tools and Models*, deals with improving the tools directly required to support the engineer. The report discusses a broad array of empirical, simulation, and analytical models. These include process models, assembly and cost models, and manufacturing system models.

The fourth Component 4 area, *Manufacturing Systems*, describes improvement efforts in integration of the design systems in manufacturing cells and systematic techniques for acquiring and analyzing data that describe the capabilities and capacities of the manufacturing systems. This includes matters related to flexible manufacturing cells, production process technologies, and design of experiments and other statistical methods.

The last Component 4 area, *Design Processes*, describes work that needs to be done to improve understanding of the design process itself. This concerns the process of design synthesis by the individual and group and the psychological and sociological phenomena in the execution of a team design process.

5. PRINCIPAL FINDINGS AND ISSUES

Based on the evidence presented during the study, the published reports cited herein, the expert opinion, and the discussion of the issues identified during the study, the study team organized the information, made judgments about its validity and applicability, and reached ten findings. Issues for which findings could not be reached are listed. Both the findings and issues are discussed in the following paragraphs.

Finding 1:

> The methods and techniques of concurrent engineering have been used to raise the quality, lower the cost, decrease the deployment time, and increase the adherence to desired functionality of a variety of products.

These products have incorporated technologies such as traveling wave tubes and pyrotechnic devices for which precise models of operation or production have not been developed. Some have been highly complex (for example, mainframe computer) and others have had very high reliability requirements (for example, large programmable telephone switch). Some products have been designed for low production runs (for example, mobile missile launcher) and others for high production runs (for example, cars). Examples also include military systems such as missile launchers and tactical aircraft.

Concurrent engineering has been used for applications that range from simple components to complex systems. The success of concurrent engineering over this variety of applications as well as the study team's understanding of how and why concurrent engineering works leads o the second finding.

Finding 2:

> Concurrent engineering has been used in the DoD acquisition process and its use was reported to have helped provide weapons systems in less time, at lower cost, and with higher quality.

Concurrent engineering methods are being used in weapons system projects at demonstration/validation, full-scale development, and in production. Nine[48] of the companies contacted during this study provided information that they are using concurrent engineering on weapons system programs. They are convinced that further progress toward a fuller implementation of concurrent engineering is possible, not only in their companies, but throughout the DoD contracting environment.

In this study substantial expert opinion and evidence support the following finding:

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48. The companies involved in weapons system development and production are: Aerojet Ordnance, Bell Helicopter, Boeing Aircraft (Ballistic Systems Division), General Dynamics, Grumman Aircraft, McDonnell Douglas, Northrop, ITT Avionics, and Texas Instruments.

Finding 3:

> There are systemic and individual inhibitors to the use of concurrent engineering in weapons system acquisitions.

The inhibitors to using concurrent engineering are found in the contractors' organizations and practices as well as in DoD's practices and policies. Capital investment decisions,[49] poor horizontal communication, local optimizations, and misunderstanding of the importance of quality are some of the barriers that must be overcome by contractors. Unrealistic cost and schedule constraints, excessive reliance on specifications and standards, and contract language that assumes an adversarial relationship between the customer and the developer are examples of government barriers to using concurrent engineering.[50]

Despite the existence of barriers, some contractor and DoD personnel are aware of the need for change and are enthusiastic about being given better tools for accomplishing their jobs. On the basis of the receptive attitude of the people involved, the study team finds:

Finding 4:

> The circumstances are right for DoD to encourage the further deployment of concurrent engineering in weapons system acquisitions.

This follows from an observation that commercial industry and, to some extent, defense industry have already begun to demonstrate success using concurrent engineering. Basic methods of concurrent engineering exist and are in use and technological support exists. Also, the need for developing weapons systems in less time at lower cost and with the assurance that they will operate satisfactorily when they are fielded is heightened by budget realities.

During conversations with contractor representatives and DoD experts the following was repeatedly stressed:

Finding 5:

> Industry experts believe that if "concurrent engineering" becomes a new area of specialization instead of a systematic approach applied across engineering disciplines, then the deployment effort will be counterproductive.

A broad vision is needed, one which can lead to continuous, sustained improvement in the engineering processes applied to all DoD weapons systems.

Issue: How can DoD avoid forcing some particular approach to concurrent engineering on its industrial base? There is a temptation to seize new concepts and to try

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49. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), pp 61-90.

50. For further discussion of barriers see *Industrial Insights on the DoD Concurrent Engineering Program*, The Pymatuning Group, Inc. (October 1988).

to apply them, even where they are not appropriate. Although one company's approach to improving their competitive situation might be successful because of some concurrent engineering method, that same method might not be appropriate for another company or for another product. Nevertheless, DoD has a strong interest in encouraging companies to continually examine their own processes and to look for ways to improve them.

Issue: Should the DoD encourage vendors to use Taguchi methods? There is broad agreement that Taguchi has made significant contributions to the practice of engineering through his concern for closeness-to-target objectives rather than within-tolerance objectives, through his identification of the need to create designs that are robust in the presence of manufacturing variations and effects of wear, and through his emphasis on the use of statistically designed experiments. On the other hand, vigorous debate about statistical methods shows that mandating use of some proper subset of statistical tools (use of certain orthogonal arrays, signal-to-noise ratios, ANOVA, accumulation analysis, response surface methods, or particular graphical presentations) is not appropriate now, and may never be appropriate. The debate concerns the following issues:

a. Should experimenters perform a group of experiments (for example, as defined by an orthogonal array) before making an inference, or should they conduct experiments one at a time making sequential inferences from some intermediate number of experiments?

b. Should the signal-to-noise ratio be used, or should other metrics such as experimental mean and variance be used to analyze the experiment?

c. Should engineers expect interaction between parameters, or is such interaction an indication of a need to redefine the parameters?

d. Is analysis of variance the best way to identify significant parameters, or are other methods such as Daniel plots and Bayes plots more effective?

e. Should the engineer expect to anticipate the optimum values for parameter settings, or will a response surface analysis show where local maxima or minima can be found?

f. Are there simpler tools such as Ishikawa's seven tools that should be used first?

g. Should companies focus on the fundamentals, such as team building and the scientific approach to problem solving, rather than adopting some cook book approach to improvement?

Although the differences between these statistical approaches may seem unimportant to a novice, there is a danger of severely impeding the effectiveness of empirical research if engineers and scientists are rigidly forced to use certain statistical tools to analyze their results. Practitioners who have learned some statistical technique that improves cost, quality, and schedule should not be criticized for using such a technique, even when the scientific justification for its use is not yet understood. One would expect that these practitioners would be receptive to suggestions for improving their experimental techniques, provided that the suggested improvements are easier to use and produce better results.

This type of situation reinforces the concern that DoD not establish any rigid checklist that associates using certain formal methods with the practice of concurrent engineering.

Finding 6:

> Continued effort is needed to develop the methods and technology necessary for advances in concurrent engineering.

The need for continued improvement in solid modeling, process-planning techniques and computer support, FEM, CFD, simulation, CAD/CAE/CAM system integration, and standardization of product description semantics was stated at many of the sites visited. Techniques are needed to support application of multiple specialized CAD/CAE/CAM tools using a single representation of the product or process. The CALS initiative has encouraged cooperative efforts to develop unified databases and integrated design tools, but the results are not yet ready for deployment in a commercial market. Many companies are capturing lessons learned in the rule and knowledge bases that support their design environments.

Finding 7:

> Several companies reported that funding for IR&D projects intended to provide an infrastructure for concurrent engineering is no longer available.

Companies that implemented elements of concurrent engineering did so either because they were faced with a crisis or else they were companies with a tradition of continuous improvement and concurrent engineering is another such improvement For companies in the first category, the crisis provided motivation, but changing the way people worked was a challenging task. Companies in the second group have established programs for encouraging people to re-examine their work continually to find improvements. In either case, based on the reports of participants the study team finds:

Finding 8:

> Implementation of concurrent engineering requires top-down commitment across different company functions. It takes several years before company-wide benefits are apparent. Early success with pilot projects helps promote acceptance of the new methods.

In each case described to us, a company implemented changes by first trying new methods on pilot projects. The pilot projects serve to identify elements of a new plan that need improvement and they demonstrate benefits of using new techniques. They also served to develop the initial cadre of corporate members skilled in the new methods. This observation is consistent with published reports of key elements for effecting change.

Finding 9:

> Pilot projects have been useful in demonstrating the benefits of concurrent engineering.

With respect to technology, the study team considered whether there were domains that should be avoided.

Finding 10:

In this study, concurrent engineering was found to be useful in a range of applications that differed in terms of the maturity and type of technology used in the product and the production process.

There are some methods, for example, that are particularly well suited to applications where the technology is poorly understood or hard to control. An example of this is the application of design of experiments to the design and production of traveling wave tubes at ITT.

6. RECOMMENDATIONS

This section contains the recommendations that follow from the findings of the first phase of the study. The study team believes that a successful strategy for exploiting concurrent engineering should build on existing successes, encourage further innovation, foster competitive pressures for progress, and avoid rigid procedural guidelines.

Recommendation 1:   *Top-Down Implementation*

> That the Secretary of Defense and OSD's principal acquisition managers act to encourage the use of concurrent engineering in weapons system acquisitions.

Companies that have successfully implemented concurrent engineering stress that the initiative for change must come from the very top. The most powerful mechanism for accelerating change is example. Therefore, OSD's acquisition managers should instill the proper management philosophy by providing leadership rather than implementation exclusively through directives.

Recommendation 2:   *Executive-Level Commitment*

> That DoD principal acquisition managers establish a policy to use concurrent engineering as an implementation mechanism for total quality management.

Top management commitment to concurrent engineering in the form of learning, understanding, and leadership with a communicated, unwavering purpose and involvement is absolutely vital to long-term success. As a first step, such management support requires a policy statement. A proposed acquisition policy statement expressing this commitment is contained in Appendix E. Management support, however, cannot end with the simple issuance of a policy statement and must be continually visible in the managers' actions. Making concurrent engineering a recurring theme in the dialogue between senior DoD and contractor executives for every weapon system will be a powerful stimulus for change. Also, DoD needs to develop a mechanism for understanding how well concurrent engineering is being implemented.

Recommendation 3:   *Pilot Projects to Accelerate Methodology and Technology Deployment*

> That OSD should encourage the establishment of pilot programs whose objectives are to demonstrate that concurrent engineering, when deployed in defense industries and applied to DoD procurements, has the potential to yield higher quality products at a lower cost and in a shorter period of time.

One of the more frequent recommendations surfaced during Phase I was the need to select and conduct demonstration programs. The programs would be used to identify:

- Concurrent engineering benefits to DoD (convince the Services that the benefits are there);

- What had to be done to facilitate the use of concurrent engineering (show by example how to employ concurrent engineering); and

- The DoD institutionalized inhibitors to deploying concurrent engineering in DoD acquisitions.

At the onset of each program, concurrent engineering benefit objectives should be established that appear to be realistically achievable based on evidence observed in commercial U.S. applications. For example, improving quality, while reducing cost and cutting the product development and design cycle in half, appears to be a realistic goal. To soften the perceived risk, some projects could be run as shadow projects until a level of confidence is reached with the concurrent engineering approaches that would allow sequential design processes to be discontinued.

The first step is to appropriately define, in general terms, the kinds of efforts to be attempted. Since there tends to be confusion caused by the labels given a program, the accepted commercial definitions for the types of programs described were reviewed:

Pilot Program: A program used to prove that a concept works to the organization running the program.

Demonstration Program: A program used to prove to people or organizations other than those running the program that a concept works.

The process of selecting and conducting pilot programs would be to:

- Review available data from ongoing and completed concurrent engineering projects (for example, those in Appendix A) to identify products, disciplines, and industrial sectors that may be more amenable to concurrent engineering;

- Select at least one project per Service with multi-Service application that has components or subsystems that are on the critical path of the next higher assembly or system, and that do not repeat the proof of application existing in commercial programs;

- Conduct pilot projects to identify benefits achievable from using concurrent engineering in a DoD procurement and where DoD investments in product and process design technologies can lead to greatest payoffs (investment menus).

Recommendation 4: *Build onto Existing Programs*

That OSD, in encouraging the implementation of concurrent engineering, build upon the beneficial aspects of existing DoD, national, state, and private manufacturing improvement initiatives.

DoD should take advantage of the progress made by various existing programs and efforts that relate to concurrent engineering. For example, the Manufacturing Technology (MANTECH) program should be expanded in scope to include support for early design of a product's manufacturing and support processes. The transition-to-production templates should be updated, expanded, and used as appropriate, to accelerate the deployment of concurrent engineering. The Malcolm Baldridge Award guidelines could

be used as a starting point for industrial improvement initiatives and the defense industries should be encouraged to participate in that program. The CALS initiative efforts to promote cooperative development of PDES should continue, with DoD playing a leadership role in resolving disputes among different disciplines.

Recommendation 5: *Education and Training*

> That DoD implement an education and training effort that starts with the senior OSD acquisition managers and then progresses to the lower levels through the acquisition chain. Once started at the top, lower levels can be trained concurrently.

Companies that have implemented concurrent engineering made a significant commitment to concurrent engineering education and training. Education and training have proven to be critical elements of the concurrent engineering deployment process and must start at the top, i.e., with the corporate officers. Any DoD effort to implement concurrent engineering similarly must have an integral training and education program that starts at the highest levels of DoD management and flows down to all levels of personnel. Since personnel spanning a broad cross section of backgrounds, expertise levels, educational levels, and responsibilities are involved, education and training curricula targeting a wide range of audiences will have to be developed and implemented.

As a step towards implementing this recommendation, OSD could create a task force that includes representatives from industry, academia, national laboratories, the Services (including military academies, graduate education programs, and occupational specialty schools), and professional groups to develop a coordinated concurrent engineering education and training action plan.

Professional societies and universities have already begun to develop education programs and texts in related fields.[51] Similarly, the Federal Quality Institute was established in June 1988 for the purpose of introducing top executives in government to TQM concepts and benefits. The DoD can take advantage of these and other resources[52] and expertise that are available in the private and public sector when planning its own curricula.

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51. For example, in his summary of *Workshop II: New York University Conference on Making Statistics More Effective in Schools of Business* (19-20 June, 1987), Harry V. Roberts of the Graduate School of Business, University of Chicago, summarizes the curricula of the graduate courses in quality and productivity at the University of Iowa, Fordham University, Columbia University, University of Wisconsin, and the University of Chicago. His summary also includes an extensive reading list. A report on the prior workshop (Workshop I) appeared as G. Easton, H. V. Roberts, and G. C. Thiao, "Making S*tistics More Effective in Schools of Business," *Journal of Business and Economic Statistics*, April 1988, pp. 247-60.

52. For example, Solicitation OPM-RFP-88-2795, Federal Supply Schedule Contracts for Total Quality Management Implementation.

Industry's experience has shown that both purchasers and suppliers must be educated in the various aspects of concurrent engineering. Contractors and lower-tier subcontractors will initially have to be convinced to invest in the education and training of their personnel. Competitive market pressures will play an important role, but DoD can promote the contractor base education and training effort by striving for a more conducive contracting environment.

Recommendation 6: *Method and Technology Development*

That DoD encourage industry to develop and improve the methods and technologies specifically required to support the use of concurrent engineering in weapons system acquisition programs.

A number of methods and technologies have evolved that support the application of concurrent engineering. Some of the more commonly used ones are described in Appendix B and case studies describing their application by industry are found in Appendix A. However, there may be application domains that are critical to DoD weapons system development for which support methods and technologies will have to be developed to do concurrent engineering. These critical sectors need to be identified and analyzed for required technology for concurrent engineering.

The conceptual framework presented in Section 4 and Appendix C of this report provides a structure for relating methods and technologies to DoD objectives. Although the list of methods and technologies appearing in the framework structure is not exhaustive, it provides a starting point for structuring a technical program. The five areas listed in the recommendation are the areas within "Component 4" described in Section 4 of this report. Within this framework, R&D efforts should consider an appropriate balance of near-term and longer-term projects using all applicable mechanisms for funding including current and new weapons systems procurements, IR&D, cooperation with the National Science Foundation and others, and contracted R&D with corporations and universities. These application-specific technologies will fit into the conceptual framework and their analysis could be used to guide investment decisions.

Recommendation 7: *Identify and Reduce Barriers and Inhibitors*

That OSD acquisition managers should initiate a process to identify and analyze statutes, rules, regulations, directives, acquisition procedures, and management practices that act as barriers or inhibitors to the adoption and use of concurrent engineering. Based on the analyses, the acquisition managers should take appropriate action to remove or lessen the effect of the barriers.

The application of concurrent engineering methods to the DoD weapons acquisition process faces a number of barriers and inhibitors of both an institutional and business nature that exist within the DoD and within the defense industrial base. The DoD barriers arise from statutes, regulations, specifications, standards, acquisition procedures, management practices, and cultural factors. While the existing system has sufficient latitude for DoD organizations to effect concurrent engineering without waiting

for new statutes, regulations, and directives to be promulgated, it does require that the government program manager and contracting officer be willing to assume some risk and allow the contractor a higher than normal degree of project management latitude. Thus, the use of concurrent engineering in the DoD weapons acquisition process can begin immediately and, in some situations, already has. The widespread use of pilot projects across weapons systems is one mechanism for addressing barriers and inhibitors. DoD senior acquisition managers' active involvement in the reducing barriers and inhibitors will increase the rate of adoption of concurrent engineering.

Contractor business practices also are responsible for a number of barriers. Although many contractor barriers fall outside the direct control of DoD, some can readily be affected by the DoD since they originated in response to DoD acquisition regulations and practices. In many situations DoD can use its influence to effect changes within the contractor community that will create an environment more conducive to concurrent engineering.

In Phase I, the study team noted several classes of barriers to concurrent engineering which are identified below. This listing includes only some of the significant barriers and is not exhaustive.[53]

Fractionated DoD acquisition organizations and deliverables. Functionally specialized requirements have resulted in functional areas, or "ilities"[54] being treated as separate product areas within a procurement. The tendency of each "ility" to optimize its own functional area has led to the formation of stovepipe[55] organizations, to manage each "ility" and its resultant product (e.g., specification, report, analysis, etc.). A strong systems engineering approach to integrated product and process design should replace separate "ilities" in the deliverables, and would prevent concurrent engineering itself from becoming just another "ility."

Funding profiles that preclude early production process development. The present procurement system does not allow the expenditure of research and development dollars for production design, which in concurrent engineering is done at the front end of a project. Therefore, OSD must advocate a change in funding profiles.

Overly detailed specification of product and process. Present procurements define the deliverable through a series of detailed product and process standards and specifications. These standards and specifications frequently act as bounds which

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53. For additional discussion of barriers, see *Industrial Insights on the DoD Concurrent Engineering Program,* The Pymatuning Group, Inc. (October 1988).

54. The term "ilities" derives from functional areas such as testability, reliability, supportability, etc., whose consideration is required as part of most DoD contracts.

55. The term "stovepipe" refers to the existence of groups of people, usually specialists in some discipline, who communicate almost exclusively with equivalent specialists across organizational boundaries. Members of such groups, who fail to communicate within a team that is responsible for developing a system, have been cited as a reason for late changes and delays in schedules.

constrain the contractors' ability to use new and innovative technologies and processes and tend to act as a ceiling rather than a floor on quality. Existing process definitions contained in technical data packages should be advisory, but optional, information. The solicitation package should allow bidders to propose unique designs which meet the performance and form, fit, and function requirements of major subassemblies. Standards and specifications relating to processes should be advisory rather than mandatory. Performance specifications may be supplemented by form, fit, and function requirements of major subassemblies to ensure interchangeability for field repair and to minimize the number of new parts entering the supply system.

Lack of economic incentives for contractor investment in productivity improvement. In the existing DoD procurement environment, contractors have few economic incentives to invest in capital equipment and engineering implementation for continued product and process enhancement. DoD practices that act as a disincentive to contractor investment include short-term contracts with uncertain quantities and restrictive profit policies. By contrast, in the commercial sector, a contractor's willingness to invest in concurrent engineering methods is driven by the opportunity for a higher profit margin and an increased market share.

Process improvement is not recognized and rewarded during the source selection process. Currently, competitive proposals are evaluated principally on a product performance and cost basis. When a contractor proposes a significantly better price, shorter delivery schedule, or lower level of effort than that proposed by the other offerors, his bid is considered suspect. Evaluators sometimes conclude that the offeror either did not understand the requirements completely or that the proposal constitutes a major overrun waiting to happen. To overcome such inequities, the evaluators should examine the contractor's plan for improving the process and assess his credibility on the basis of his prior performance.

A. CASE STUDIES

This appendix relates some reports of success in using concurrent engineering. Several of the cases report limited initiatives withing larger corporations. The stories do not, unless specifically stated, indicate that an entire corporation is using similar methods. Finally, the case studies are success stories, they include application of elements of concurrent engineering. If some of the applications are viewed in isolation, the connection to concurrent engineering may be weak. Taken as part of a company's plan to improve quality, reduce cost, and cut the schedule, they can be considered as part of concurrent engineering if the plan emphasized early consideration of downstream processes.

Several of these initiatives were started independently of any concurrent engineering program. They are included because they represent elements that contribute to achievement of the goals of concurrent engineering.

A.1 Aerojet Ordnance Company

Company   Aerojet Ordnance Company

Situation   Based on recognition that the issue of "quality" had to be addressed throughout the company, the President and Executive Vice President attended the 1 week American Supplier Institute (ASI) course. They enthusiastically embraced statistical process control and other new management and engineering tools. Immediately thereafter, the company top management staff was exposed to the 1 day introductory course, after which all managers and supervisors attended 1,3, or 5 day courses.

Approach   Aerojet Ordnance looked at quality in five categories—management, products, operations, methods and tools, and cost of poor quality—and adopted the following seven elements of a Total Quality Management Program:

- Leadership,
- Management by policy,
- Use of traditional/new quality tools,
- Statistical process control (SPC),
- Concurrent design/engineering,
- Quality function deployment (QFD)/teamwork,
- Taguchi methods of designing experiments.

Results   Aerojet Ordnance is making a cultural change, the new culture emphasizes statistical thinking with more emphasis on leadership. SPC was used extensively in the factory. As a result of extensive application of SPC and its TQM program, inspection will soon be eliminated on many processes and the in-plant role of government Defense Contract Audit Service (DCAS) groups will be significantly

reduced. Aerojet will then be recognized by the Army as a fully certified contractor. Three Taguchi experiments were described during the workshop.

Experiment 1

The first experiment involved pyrotechnic products (tracer ammunition). A 25mm projectile (tracer) has functional requirements for ignition and continued burning. Aerojet was receiving pyrotechnic components for the rounds which satisfied the purchase specification, but when assembled into a tracer projectile provided unreliable burn times. There was a problem; 400,000 pellets were on hand but the burn time for the pellets was too short. The company looked at the process for loading the pellets into the projectile. They looked at the punch, the levels of pressure, the type of pellet, the interaction between them, and burn-time data. They used signal/noise ratio as a figure of merit. They ran four tests.

Result for Experiment 1

By doing a Taguchi experiment on the loading process, they were able to salvage the lot of pellets. The initial savings was $500,000. There are continued savings above this figure and Aerojet continues to use the same components.

Experiment 2

The second experiment involved a generic product area of pyrotechnic devices to establish a product technology database. Using the normal Taguchi progression, that is system design, followed by parameter design and tolerance design, Aerojet looked at the entire tracer pyrotechnic business across all product lines. They did a preliminary investigation as part of exploratory development and designed a set of experiments to identify critical parameters. The experiments looked at several conditions, and included noise factors. Aerojet didn't analyze the results for a specific product, but they built a broad technical database. When a product came along they used the technical database to develop it. An exhaustive experiment of the factors considered would have required 1.6 million experiments. Using orthogonal arrays, Aerojet did just 27 experiments.

Result for Experiment 2

Developing a new round using their traditional methods, normally costs over $2,000,000, takes over 2 years, and provides a product that is not robust. Three new products developed with the new method. Using the new technology database (developed with the Taguchi experiment) required only 1 month of verification testing (a 98 percent improvement) for the new products. A measure of the quality improvement of the new products is an improvement of the mean/(standard deviation) quotient by a factor of 5. The present value of the technology database is calculated as $60,000,000, based on expected future sales of products similar to those now in

production.

Experiment 3

The third experiment involved poor production quality from GOCO plants which were making the ADAM mine for the Army. Nonconforming product was a problem. Nineteen out of 25 lots were rejected (40,000 rounds per lot). A joint team of government and industry had been trying without success to find the cause of the problem. Although Aerojet had not developed this product, Aerojet was called in to apply Taguchi experiments to the testing. They took 3 months to prepare for and conduct experiments to identify critical parameters. They identified 13 controllable factors and set three different levels for each factor (all except one were within tolerance). They fired six rounds for each experiment. They identified four factors of greatest improvement and identified how building the round with those factors at the best levels would provide virtually 100 percent good rounds.

Result for Experiment 3

These predictions were validated in field testing. Using the parameters identified in the experiments, 54 rounds were produced and tested without a failure. This was the first time in the history of the product that 100 percent yield had been observed over a reasonable time period. Another 54 rounds were produced using parameter setting where the experiments predicted a yield of 50 percent. Twenty-seven of the rounds failed the test. Production lines are now working to capacity building good product. There have been no reported problems in 8 months. The tech data package is being revised. The other nine factors were not important and they could be relaxed. The plants had previously been under SPC and had a c_{pk}[56] of 2.0.

Aerojet uses SPC and they are working to become a certified contractor. Based on their experience with the ADAM mine, Aerojet concluded that SPC alone is not enough. They use Taguchi experiments to find correct *target values*. If they are certified, the DCAS people will leave the plant and Aerojet will produce products under warranty.

Remarks The Total Quality Management effort must come from the top down. It takes several years to establish a company-wide habit of quality improvement. The return on investment in quality improvement is among the highest available to management. Quality has to be the first priority for improvement.

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56. See Appendix B for a definition of c_{pk}.

A.2 American Telephone and Telegraph

Company   American Telephone and Telegraph (AT&T)

A broad range of quality improvement methods are used at AT&T, including robust product and process design, traditional design of experiments, failure mode analysis, reliability prediction and analysis, fault tolerance, the seven basic tools, hardware and software design reviews and inspections, and process management and improvement.

The following examples summarize a few applications of these methods. They are not a cross section of the applications at AT&T.[57]

Division   Two divisions were reported:

Design AT&T Bell Labs, Indian Hills West, Naperville, IL

Manufacturing Oklahoma City Works, Oklahoma City, OK

Product   Circuit Pack Design for the 3B series computer.

Approach

Process Management   Get control of the process and then find ways to improve it. Total Quality Control. Process ownership - someone owns the process independent of the product.

Technology   Develop a family of computer-aided design (CAD) and computer-aided design verification (CADV) tools. Use the tools early in the design process to ensure designs are functionally correct, suitable for the manufacturing process, and testable.

Multifunction Team   All circuit pack physical design, support library, component engineering, CAD Tool and System development are in one department. The process owner is a member of that department.

Situation   AT&T experienced a cultural shock during divestiture, but that was not cited as a reason for the process improvement effort. They were experiencing problems with low yields in the production process, notably during a transition from design to production. Typical first pass yields for circuit packs at system level test during early production runs were 50 percent. Furthermore, it took a considerable length of time to achieve 90 percent test pass rates. During the first 18 months, the multi-layer printed circuit boards usually went through three art master design

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57. Anne Shoemaker, Supervisor, Quality Engineering Research & Technology Group, (September 29, 1988).

cycles.

Results   AT&T performed a number of organizational and process changes aimed at reducing variability. The model building facility was dismantled and the initial units were built with the equipment that was to be used later for volume production. They discovered that although the first units took a little longer to produce, they were able to ramp up to full-scale production much faster. The result was a 90 percent acceptance at the first production run, sharply reducing the effort needed for further yield improvement. The number of printed circuit board art masters dropped to two. One-pass design is the goal of design process improvement.

CADV located errors and design bugs, some of which would *not* be detected in laboratory testing. These errors include timing problems, untested parity and block transfer circuits, missing pull-up resistors, and timing margin problems.

Standard capacitor filtering strategy for surface mount technology (SMT) packs reduced the number of parts to 1/3 and reduced the cost to 1/9. On the basis of analytic studies they were able to take advantage of the physical properties of SMT and standardize on high frequency capacitors resulting in savings through purchasing and other efficiencies.

AT&T adopted 100 percent SMT strategy on all new products and uses one manufacturing process for SMT.

Concurrent CADV and laboratory testing of factory prototype is used for design validation.

The AT&T quality standard on SMT circuit packs is to be totally free of white wires. They have achieved that goal on 90 percent of the circuit packs.

Other Locations

AT&T Bell Labs[58]

- Applied Taguchi experiment to selection of parameters to improve the operating system response for a UNIX™ on a Digital Equipment Corporation VAX™ 11/780 computer. Response times were improved by 60 percent to 70 percent and variability was reduced by a similar amount.

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58. Madhav S. Phadke, *Quality Engineering Using Robust Design*, to be published by Prentice Hall, Inc. (January 1989).

™ UNIX is a trademark of AT&T.

™ VAX is a trademark of Digital Equipment Corporation.

- An experiment was conducted to improve the polysilicon deposition process for producing silicon wafers for very large scale integrated circuits (1.75 micron design rules). The experiment was part of a class project (an internal Robust Design class) and yielded a fourfold reduction in variance of the thickness of the polysilicon layer, nearly two orders of magnitude reduction in surface defects, a major yield-limiting defect that was virtually eliminated.

- The *window photolithography application*[59] was the first application of Taguchi methods in the United States and resulted in fourfold reduction in process variance, threefold reduction in fatal defects, twofold reduction in processing time (inspections could be dropped), early transition from design to production, and easy adaptation of the process to new technology (going from 3.5 micron to 2.5 micron).

Denver Works[60] Power Unit Assembly Shop: Just-in-time and Total Quality Control

- Productivity/employee increased 233 percent.

- Product velocity increased 750 percent.

- Work in process inventory decreased 64 percent.

- Process down time decreased 61 percent.

Oklahoma City Works 5ESS™

- Cost of quality decreased by half to less than 10 percent.

- Total process time reduced to 46 percent of the 1984 baseline in 3 years. Planned reductions to 25 percent by 1989.

- Defects reduced by 30 to 87 percent.

- First production run yields up from a base of 20 percent to approximately 90 percent in 2 years.

Source   Presentation by Alan Fulton at IDA Concurrent Engineering Workshop and site visit by IDA.

59. Phadke, M. S., Kacker, R. N., Speeney, D. V., and Greico, M. J., "Off-Line Quality Control in Integrated Circuit Fabrication Using Experimental Design," *The AT&T Bell System Technical Journal*, Vol. 62, No. 5, May-June 1983, pp. 1273-1309.

60. Laurence C. Seifert, "Design and Analysis of Integrated Electronics Manufacturing Systems," *Design and Analysis of Integrated Manufacturing Systems*, National Academy of Engineering, Washington, DC (1988) pp. 12-33.

Remarks

- Taguchi method, also known as robust design method, is extensively applied in integrated-circuit process engineering and component design both in AT&T Bell Labs and in the manufacturing facilities.

- Concurrent engineering at Indian Hills West is part of the advanced development process.

- All projects at Indian Hills West (Naperville circuit pack) are committed to CADV, often doubling[61] up-front circuit design staff.

- CADV is absolutely necessary to meet R&D quality[62] goals.

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61. Although more people are needed for part of circuit design and simulation effort, total effort is decreased. That is, the shortened development time compensates for the added people.

62. AT&T has a goal of improving quality by a factor of 10 in 5 years.

A.3 Boeing Aerospace Corporation

Company   Boeing Aerospace Corporation

Division   Ballistic Systems Division

Situation   In the years 1978 through 1985, Boeing failed to win a number of Full Scale Development procurements. Although Boeing consistently scored high on technical merit and product quality, its cost was not sufficiently competitive. In October 1985 Boeing executives met and initiated a coordinated BA-wide effort to reduce operating costs and improve efficiency. As the cornerstone of its strategy, Boeing focused on improving the effectiveness and efficiency of its process.

Approach   BA calls its approach to simplifying developmental practices Developmental Operations (DO). DO is defined, in part, as a "renewal" process whereby marginal "value-added" process is replaced with process that enables step-function improvements in efficiency. A complete end-to-end examination of their current developmental process resulted in display of their baseline "as-is" approach. Using quality improvement "process management" evaluation techniques, they isolated "barriers" and marginal "valued-added" effort to aid in creation of the new desired "should be" process. The DO approach features (84) internal improvement "initiatives"—changes in current practices, process, and discipline suited to universal program application while permitting flexibility for any given contract.

At the heart of the DO approach is the Product Development Team (PDT) initiative. The PDT is a multifunctional team with a common goal of developing a specific product. Typically, a PDT includes representatives from Engineering, Logistics, Manufacturing, Materiel, and Quality Assurance. Other expertise is brought on-board as required, and all customer representatives have an open invitation to attend meetings. Each PDT representative has the authority to commit his or her functional organization. The PDTs "own" all contract requirements. Each member of the PDT participates and authorizes the release of drawings, requests for procurements, and other implementation documentation.

A typical development effort will have multiple PDTs. PDTs are created as the need arises to address major sub-elements of the development effort. The PDTs set their own meeting schedules, but at a minimum meet biweekly. All team members are required to attend or to notify the team leader that they will be absent. Emphasis is placed on short lines of communication, real-time visibility, and consensus management. All meetings are kept brief to maximize group effectiveness. More involved problems are resolved at side meetings with only the necessary people present. The meetings follow a predetermined agenda and minutes are kept of the matters discussed and decisions made.

All PDT members undergo team training and each PDT has a team leader. The team leader is responsible for team administration and represents the team during management reviews. The team leader may change as the program progresses. For instance, during requirement development, the team leader is usually from System Engineering or Logistics. During the design stage, the leader is from Design Engineering. During fabrication, from Manufacturing or Materiel, and during the test phase from Test Engineering or Quality Assurance. The team leaders meet monthly to exchange ideas, reaffirm team interfaces, and generally learn from each other.

Process and product quality is heavily embedded in the DO approach. A balanced quality program exists and is derived from the premise that all individuals share in the responsibility of assuring product integrity, quality, and configuration control. Emphasis is placed on the fact that people, not systems, are responsible for their output. Line inspection requirements are limited to critical product and process elements as defined by the Quality Assurance engineer working within the PDT. The responsibility for quality of routine manufacturing operations, procurements, and engineering design is placed with the appropriate functional organization using self-audit and mangemen. indicator techniques, and overseen by the PDT as it relates to team assignments.

BA supports the PDTs with extensive training and equipment investment. Every member must undergo an eight-hour training course which emphasizes team-building concepts. Boeing has acquired new computer and data-processing equipment to further automate engineering, drafting, manufacturing, and business system needs.

The implementation of DO required a major cultural change at Boeing. The difficulty of this task was recognized and Boeing elected to retain United Research Company (URC) as consultants for this effort. URC assessed Boeing's current culture, organization behaviors, etc., and determined an appropriate course of action. URC, working with Boeing, devoted seven man-years of effort to helping Boeing manage the cultural change within the Ballistic Systems Division (BSD). Boeing found that continued upper management commitment to DO was essential to its successful implementation.

Results   Developmental Operations have enabled Boeing to recapture its competitive position within the market. Labor rates have been reduced by as much as $28 per hour. Boeing has been awarded several major developmental contracts since 1985. Furthermore, it is realizing 16 percent cost reductions below bid (and the bids were 30 percent lower than traditional for this work) on three new programs to which the DO concept was applied. Some areas show reduction of up to 50 percent.

Overall process quality has greatly improved. Team usage of a computer-aided tool, Verified Item List System, has permitted early error capture and correction.

Critical inspection features are now identified directly on all drawings. Boeing is down to about one engineering drawing change per drawing sheet from previous highs of 15 to 20 corrective changes. The floor inspection ratio dropped from about one hour of inspection per 15 hours of labor to one hour per 50. The cost of quality is 60 percent less than that within a standard operating environment while maintaining 99 percent defect-free hardware performance.

Parts and materials lead time has been reduced by 30 percent. Seventy percent of all needed parts and materials are available in the factory within five days of a request, compared with 60 to 90 days previously. Material shortages have been reduced from 12 percent to less than 1 percent. New relationships with suppliers have given Boeing access to real-time information about suppliers' stock.

Automation reduced the time necessary to iterate designs. The design analyses, which originally took three to four engineers two weeks to determine each data point for doing trade-offs, is now accomplished in 38 minutes using an Apollo 550.[*] The newer Apollo 10,000[*] will further reduce the time to four minutes. These sophisticated tools permit designers to begin considering "ility" implications much earlier in the design cycle.

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[*] Apollo 550 and Apollo 10,000 are trademarks of Apollo Computer Company.

A.4 Deere and Company

Company   Deere & Company

Deere & Company is the world's largest producer of agricultural equipment and a major producer of construction and forestry equipment. Deere & Company is headquartered in Moline, Illinois with domestic factories in Iowa, Illinois and Wisconsin. Management is stable, developed primarily by promotion from within the company, and the production workers are unionized, represented by the United Auto Workers. The company spends 6.5 percent of gross sales on research and development, and 0.5 percent of gross sales on education and training. The John Deere Dubuque Works are located in Dubuque, Iowa and manufactures construction and forestry equipment. This case study is based on a site visit to the John Deere Dubuque Works.

Division   John Deere Dubuque Works

Situation   Deere & Company initially embarked upon a program of changing its design and production methods in an effort to simplify a design process and production facilities that had become overly complex. New products took 7 years to develop, a time too long to result in competitive products. Material flow patterns within the facility had become overly complicated and long and the in-process inventory was too large.

Although the roots of the changeover can be traced back to managers in the mid 1970's who had a vision of the role of quality in the future, the effort was sharply focussed by a worsening financial situation in the 1980s. At its peak in 1980, Deere & Company had annual sales of $5.5 billion, and employed 61,000. By 1986, sales had slipped to $3.6 billion, and the number or employees had been reduced to 37,000. Earnings dropped from a profit of $228 million in 1980 to a loss of $229 million in 1986.[63] Deere & Company's worldwide competitive position had eroded in the face of stiffer domestic and foreign competition.

Approach   Deere & Company instituted a revised design and production system, the John Deere/Group Technology System (JD/GTS). Group Technology recognizes that many aspects of manufacturing share similar characteristics. By grouping these characteristics, JD/GTS aims to maximize the utilization of equipment and manpower, to minimize work-in-process, and to enable high volume economies in low-volume situations. This involves moving away from large functional, process-based departments and divisions to individual small departments and operating units. These manufacturing cells perform nearly all of the operations on their

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63. This reflects impact of a strike.

assigned part families and eliminate inefficient cross-flow among departments. The cells are flexible and allow the production line to rapidly react to changes in market and internal needs.

In addition to JD/GTS, the Dubuque Works also changed to just in time (JIT) materials management and undertook competitive benchmarking. Competitive benchmarking involves the disassembly and analysis of competitors' products to determine what it costs the competitor to produce these products. The extent of information sharing among competitors in this product field allows competitive benchmarking to function.

The management at the Dubuque Works found that to successfully implement JD/GTS, the utilization and attitude of the personnel and the role of technology had to change. The required organizational changes were identified and accomplished almost completely using internal resources and without outside consultants. Reaction to the changes was mixed. Upper management and the production line workers, including unionized labor, supported the changes. Middle management, on the other hand, resisted the changes. Some middle-level managers had to be reassigned or encouraged to take early retirement. A significant re-education effort was necessary across the whole plant.

Computer technology was installed and integrated across design, production and customer service. The Dubuque Works are linked throughout by a sophisticated computer network that links a wide variety of transmission media (that is broadband, Ethernet, twisted pair) that operates at differing transmission speeds and interface a variety of computer types. The network connects all the facilities, including the factory floor, power generating station, administrative offices, and design areas. Software and processes can be accessed throughout the system. Furthermore, the network is linked to networks at other Deere facilities.

The extensive networking allows a concurrent approach to product design and engineering. Production engineers designing tooling fixtures access the same databases as the design engineers who design the components to be assembled on the fixtures. Changes by one engineer are instantly available to the other engineers.

The Deere & Company approach recognizes that changes are inevitable. Rather than imposing early design freezes that resist change, only limited aspects of the design, such as the fixture clamping points, are frozen. In this way, fixture design and tooling can begin much earlier in the development process. Changes in product design have minimal effect on tooling requirements. For example, computer-controlled sheet metal cutters fashion components based directly on CAD-developed design drawings.

Tooling fixtures are designed to be usable across product lines. In this way, a production cell can process more than one product variety without retooling. In

the course of a day, subassemblies for different products can be mixed in tandem on the line with no problem.

Deere & Company has developed an in-house, rule-based expert system to create manufacturing data and numerical control (N/C) part programs for rotational parts. The system runs on a UNIX ™-based engineering workstation and uses part geometry form product engineering as its input. Information from the knowledge base determines the manufacturing method, selects the tooling required from a tooling database and starts to create the N/C program. Operator intervention is minimal and only required to override the method computed by the expert system. The resulting data is automatically loaded to databases for access by production personnel and the DNC system.

The Dubuque Works offer telephone-based customer support. Service shops and dealers throughout the country can call in with questions that are fielded by a cadre of Deere technicians. Customer concerns, problems and questions are resolved and also entered into a database that is cross-indexed and available for future reference. This database also feeds to the design and production engineers who monitor it for possible design problems in existing product lines. The flexible manufacturing configuration permits a very rapid correction of most problems flowing from a design flaw. In many situations, once the source of a problem is identified, the production line can be immediately modified. The very next item off the production line can incorporate the customers' feedback.

The extensive use of networking and databases has permitted the almost complete elimination of hardcopy drawings as the means for managing component specifications. The information is stored and updated electronically. The system automatically identifies all the drawings that are affected by any change and that may need updating. This has resulted in fewer errors per drawing, particularly the errors that were caused by improper copying of numbers between drawings or the failure to update all the drawings affected by a change. Hardcopy drawings are generated only as needed.

The Dubuque factory has taken a cautious approach to the introduction of production line automation. Rather than embarking on a wholesale transition to robotics, they have targeted the introduction of from four to six robotic systems per year for the Dubuque Works over the next 4 to 5 years. They avoid using new products to introduce automated tooling. Every modernization feature has to be justified on its own, not simply because it will be used to fabricate a new product.

Results   As a result of these changes, the development time for new products has been reduced by 60 percent. The associated cost savings were 30 percent. They reduced engineering builds from 3 plus pre-production to pre-production only. The ratio of indirect to direct employees is the best it has ever been.

Standardization across product lines and homogeneous production and assembly reduced setup time, changeover time, and parts in inventory. The number of different parts that had to be fabricated and stocked was reduced by 60-70 percent. The amount of work in process dropped so drastically, that the Dubuque Works no longer use the acres of parts racks they previously needed.

Some aspects of quality have improved. Products are more responsive to user needs. Production line workers have assumed more responsibility for ensuring the quality of their work. The company found that with multiple iterations of inspection people tended to get sloppy. The early inspectors assumed that the subsequent inspectors would catch defects, while the subsequent inspectors assumed that the defects had been caught by the prior inspectors. The number of inspectors has been reduced by two thirds. Quality assurance has taken on the role of a problem solver rather than of a policeman. At about 1980, scrap and rework costs decreased about 60 percent. Beginning about 1982 quality standards (for example finish, fit-up, tolerances) have been raised significantly while holding scrap and rework costs level. Deere plans achieve further reductions through design of experiments and SPC. After-delivery costs of quality (warranty and service) have been constant. Programs to reduce these costs include the Dealer Technical Assistance Center (DTAC) a center linked to the electronic design database. Surveys of backhoe loader customers reveal expectations of an additional 50 to 100 percent service life for Deere products compared to some of the competitors.

A.5 Grumman

Company Grumman Corporation

Division Grumman Aerospace Division

Location Bethpage, New York

Situation Grumman formed a "task teaming" arrangement for the McDonnell Douglas C-17 Control Surface subcontract. Teams were established by structure function as opposed to individual control surface, e.g., Cover Team, Hinge Fitting Team, Spar Team, etc. In other words, a team was not assigned to each end item produced but worked on the same function for each end item.

Approach Each team consisted of permanent members and part-time members as shown below.

Permanent Members	Part-Time Members
Design	Weights
Stress	Finite Element Analysis
Tooling	Dynamics
Numerical Control	Materials & Processes
Drafting	Methods
Master Dimensions	Quality Control
	Support
	Reliability & Maintainability
	Procurement

In addition a "team" of group leaders was formed to ensure communication and to provide personnel handling and reporting required by Grumman's matrix management system.

The permanent members were seated around CADAM/CATIA work stations; the part-time members and group leader team were seated in nearby central area and joined permanent teams as required to input and approve designs. A central area for drawing approval and release was also in the area.

Results Grumman is pleased with the results and feels that task teaming has helped keep the FSED schedule on time and reduce the development risk. Benefits that have accrued to date include:

- Reduction of engineering changes due to error by a factor of ten.

- Increased responsiveness to customer changes.

- Increase in morale of program personnel.

Production benefits are not known at this stage of the contract but no production problems are expected.

Problems that arose and their solutions were:

a. Problem Insufficient direction of inexperienced personnel because of dispersal of disciplines throughout various teams.
    Solution Teams were consolidated to minimize the number of disciplines with one or two members. Inexperienced personnel were placed in larger teams and group leaders and lead people made an effort to maintain contact with inexperienced personnel.

b. Problem No one person has knowledge and understanding of the overall control surface because teams rotate to all surfaces to work on similar tasks.
    Solution Key members of the Cover Team were assigned to each control surface and were responsible for overall coordination of tasks relating to that surface.

c. Problem Potential for tedious repetition of tasks.
    Solution Team members were required to communicate with other teams and participate in the design and analysis of interfacing structure in addition to primary tasks. Solutions to a variety of problems were required during the 6 month design phase.

A.6 Hewlett-Packard Company

Company   Hewlett-Packard Company

Division   All divisions, worldwide

Product   HP designs, manufactures, and services electronic products and systems for measurement and computation. These products include computer products, test instruments, analytical instruments, and medical products.

Situation   HP has typically enjoyed a good reputation for designing and manufacturing quality products which meet the needs of its customers. Nonetheless, over the years they have experienced rising customer expectations, excessive costs of poor quality and increasingly strong quality competition. These forces have increased HP's attention to quality the past 10 years.

Action   Several years ago, HP began implementing its new approach to improving quality, called Total Quality Control (TQC). HP defines TQC as a management philosophy and operating methodology that is totally committed to quality. It focuses on continuous process improvement through universal participation, resulting in increased customer satisfaction. TQC means that quality control efforts begin with the design of the product and are complete only with the customer's satisfied use of the product. Thus every function is involved in quality control: the marketing group in providing an analysis of the need for the product; the designer of the product; the vendor and buyers of materials; the manufacturing and testing of the product; handling, storing, packing, shipment and delivery of the product, the maintenance, reliability, and repairability of the product; the market analysis of the user's satisfaction with the product; and finally the subsequent design and redesign of new products—the whole cycle again.

There are five main components of TQC which join together to create a synergy of continuous process improvement. If any one of the main components is missing or lacking, the remaining efforts are far less effective. These main components include:

> Management Commitment
> Customer Focus
> Statistical Process Control
> Systematic Problem Solving Process
> Total Participation

Top management commitment in the form of learning, understanding, and leading the TQC efforts with a communicated, unwavering purpose and management involvement is critical.

Customer focus includes defining quality in terms of the customer's needs, listening to the voice of the customer, and transforming that voice into desired products and services. In addition, everyone and every job has a "customer"

whose needs must be met.

The use of QFD to help transform cust 'er requirements into better designed products is spreading throughout parts of h.r with successful results.

SPC involves the application of a wide range of powerful statistical tools and techniques to help people understand, manage, and economically improve their processes and systems throughout the organization. These tools include simple tools such as process flow diagrams, Pareto charts, control charts, etc., to more sophisticated techniques such as statistically designed experiments, reliability analysis, ARIMA model forecasting, simulation, variance components analysis, and others. Without these tools, TQC results would be severely limited.

A systematic problem solving process provides a mechanism for solving problems in a sequential, systematic fashion. It is the pathway of continuous process improvement. HP follows the Deming "Plan, Do, Check, Act" (PDCA) cycle. Other problem solving processes such as Kepner-Tregnoe also have been useful. Further, standardized approaches to process documentation, review, and traceability are used.

Total participation means everyone within the organization and everyone outside of the organization who interacts with the company, such as suppliers, plays an active role. This is accomplished through group training, conventions, publicity, promotion, and so forth.

As part of its TQC efforts, HP is working more closely with its suppliers. A revised vendor qualification program is being used. The TQC effort is underway in various stages throughout all divisions of the company. It begins with management commitment, intensive training, application of the principles and tools usually on a pilot project basis, and gradual spreading and reinforcement throughout the organization.

Management has begun applying the TQC tools to the process of management, using the technique called Hoshin Kanri. In particular, Hoshin Kanri significantly helps with the organization and execution of strategic planning issues throughout all levels of the organization.

Results   Many positive results have been recognized from the TQC efforts. There has been a large increase in quality awareness and customer focus. Untold improvements have been recognized throughout all departments and divisions of the company. For example:

- The composite field failure rate of all HP products has decreased 83 p...cent over the past 8 years.

- Scrap and rework costs have been drastically reduced in many divisions. One wave soldering process reduced its defect rate from 4000 parts per million (ppm) to 3 ppm. Other areas have experienced reductions of 80-95 percent.

- Manufacturing costs have been reduced as much as 42 percent.

- Parts inventories have been reduced as much as 70 percent.

- Manufacturing cycle times have been reduced as much as 95 percent.

- Product development times have been cut up to 35 percent.

- Productivity has increased as much as 300 percent.

- Physical plant requirements, including floor space, have been reduced significantly in many cases. One division reported that it has increased shipments 400 percent over the last several years without having to add any floor space.

- One field repair station reported reducing its repair turn-around time 80 percent.

- The finance department at one division trimmed its financial close cycle 33 percent.

- TQC applications in field sales operations have improved sales effectiveness.

The widespread, continuous use of the simple SPC tools has been critical to achieving the gains cited above. In addition, the application of statistically designed experiments has resulted in millions of dollars in savings. HP has conducted thousands of factorials, fractional factorial, central composite, and response surface methodology designed experiments over the past several years. Very few of these experiments (less than 7 percent) have required any capital investment. A few examples of documented savings include $1,000,000 in one year warranty savings for one product; $260,000 per year savings in a gold plating process; 88 percent decrease in labor and material cost in another chemical plating operation; $650,000 savings on a solder machine process; 75 percent error reduction in process in an automatic component insertion process; 35 percent reduction in process development time for a product. HP has found that these classical designs for conducting experiments do an excellent job of catalyzing and rapidly advancing engineering knowledge, leading to faster technological breakthroughs and process improvements.

Throughout HP there is an increasing use of JIT (Just-In-Time) and Kan-Ban methods of manufacturing. These methods have sharply increased manufacturing quality and responsiveness to changing order quantities, and reduced scrap, rework, inventory, floor space needs, and manufacturing cycle times.

Also, there is widespread use of New Product Introduction (NPI) Teams. These teams include representatives from R&D, marketing, materials engineering, manufacturing, production control, purchasing, production engineering, etc. Their use has greatly improved the transition of products from development through production and sales, resulting in far fewer manufacturing problems,

fewer engineering change orders, and more consistent product performance for the customer.

Observations

- Top management leadership is absolutely vital to a successful concurrent engineering effort. Top management must educate itself first on the philosophy, principles, and some tools before it can effectively lead the effort through their organization. Verbal support only will bring only minor improvements. The quality management philosophies of Deming and Juran have been excellent sources for HP.

- Major improvements are obtainable almost immediately, but the really monumental gains take several years of hard work and perseverance. At that point, the rewards become very impressive.

- The small, incremental improvements made everyday, with the help of widespread application of the simple tools and an untiring focus on continuous process improvement are what lead to the big, long-term gains.

- It is easy to place too much emphasis on the tools and techniques when getting started. The philosophy and principles are far more important to learn and understand first as these provide the guidance for applying the tools.

- Many, if not most of the benefits and rewards are not measurable or visible on the bottom line. These benefits are unknown and unknowable, yet are extremely important to the visible gains. They include improved communication, increased ability of people to work together, enhanced morale, more effective use of people's knowledge for the benefit of the company, the multiplying effect on sales of a satisfied customer, the multiplying effect that improved materials, procedures, processes, tools, maintenance, training, etc. have on the production lines, and so forth.

- The application of TQC is not only beneficial to manufacturing areas but equally beneficial to administrative areas as well.

A.7 International Business Machines

Company   International Business Machines (IBM)

Locations   Poughkeepsie, NY and East Fishkill, NY

Poughkeepsie, NY

Product   Mainframe computers (IBM 30XX product line)

Function   The Poughkeepsie mechanical packaging group provides design and packaging of system power, mechanical, and thermal (PMT) for the 3090 product line. The product development took place at the Poughkeepsie laboratory, the manufacturing operations were accomplished at the Poughkeepsie plant.

Situation   The IBM 3090 has been, and continues to be, a successful product line. The design group, however, was concerned about the high level of continuing product engineering support needed for engineering changes (EC) after the design was released to manufacturing and the product passed the general availability (GA) milestone (high rate production). (ECs can consume an effort equivalent to redesigning the product several times after it enters production.) High numbers of ECs occurred despite a well established corporate policy of early manufacturing involvement (EMI) in product development. The process was serial; communication at the boundaries (between laboratory and manufacturing) was not as effective as possible.

Approach   The Poughkeepsie laboratory, working in conjunction with the plant, established a facility called the Total Concept Facility (TCF) where a team made up of specialists from different disciplines concerned with designing, producing, and supporting a product could work together throughout all the phases of product design. The team included approximately 70 people, with heaviest participation from development and manufacturing. Other representatives from marketing, quality assurance, and field engineering complete the team.

Formation of a team was not a radical departure from previous practice. There has been an ongoing practice of cross-assignments between management in development and manufacturing.

Product development team members are co-located at the TCF and the cooperative process is institutionalized. With the TCF, teamwork is more continuous; manufacturing representatives participate in the product's requirements definition and conceptual development. At the TCF, team members use three-dimensional (3D) digital models of the product so that manufacturing representatives can visualize the design and plan the assembly process.

Team members work together to establish requirements (the equivalent of before Milestone 0 for DoD). Requirements are the result of concurrently analyzing

customer needs, lessons learned from IBM and competitor's existing products, and the results of an engineering analysis of "best of the breed" capabilities.[64] Requirements included firm targets for performance, cost, and schedule. Factors affecting ease of installation, and goals for reliability,[65] availability, and serviceability (RAS) are established. Performance objectives include firm targets not only for traditional performance measures but also for part count reduction, and lower assembly times and costs.

The process of establishing requirements is top-down both for the targets and for the "best of the breed". Desired functions are compared to product features, manufacturing capabilities, and cost estimates. The process is not new with the TCF, but it was done with greater precision and to a greater level of detail than ever before. Within the TCF, the first two phases of design, requirements definition, and conceptual design, consumed approximately 25 percent of the effort. Independent of the TCF, supplier/customer relationships are established early in the design cycle.

The laboratory established a CAD-tool development group to provide computer support for the design and release functions. Coordination between the tool developers and tool users (product designers) was encouraged by having both report to the same manager.

The tool development group tailored a solid modeling system which had been developed at IBM's Yorktown Heights Research Facility. The tool developers work closely with their customers (the development team) to support a design system that includes

- three-dimensional (3D) solid modeling,

- two-dimensional (2D) design and drafting,

- cable design and routing, and

- packaging design (including databases that reflect experiences gained in component and part selection).

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64. The "best of the breed" is a set of targets for quality, performance, price, ease of installation, reliability, availability, and serviceability (RAS). The values are the result of analyzing individual features of competitors' products, projecting the expected advances during the life of a product, and creating a hypothetical product which combines the best features from several sources.

65. Reliability of a new product at GA is required to equal or exceed the reliability of the product being replaced. Firm fixed times for system installation (less than 6 hours) is viewed as an important customer requirement.

The design system has interfaces to manufacturing through soft-copy release, to materials management through bill of material generation, and to a corporate central file (CCF) that can be queried by engineers for data on parts usage throughout the corporation. The TCF development support system also provides information for management tracking and support.

The proximity of the tool suppliers to the users allows rapid development and tailoring of tools. The first priority was to tailor design system to support PMT design and packaging. Improved visualization resulting from use of solid modeling had a significant impact on design quality. Development of feature-based design support has been a major advance. Feature-based design systems include knowledge about the attributes of generic components of a design and rules that can be applied to select specific parts based on the values of their attributes. Feature-based systems may also support the notion of a hierarchy of pieces and parts.

Using a feature-based system, designers synthesize a design by selecting generic components and describing their attributes. The system screens its database and presents the designer with a list of specific parts which perform the desired function and satisfy the requirements.

For example, a feature-based system captures some sense of the verb "to fasten" which includes a model of parts being fastened, an item to accomplish the fastening, parts of the fastening item, their order of assembly, their relationship to the parts being fastened (such as there must be a hole for a bolt), and any attributes of the parts that are important (diameter of a hole, diameter of a bolt, corrosive properties of bolt and part being fastened, etc.).

Using feature-based design, an engineer might select some desired product feature such as a fastener. The design system searches the database and provides a list of all approved fasteners that could be used at a certain point in the design. The parts list will usually include only those parts satisfying some set of design rules. The engineer has the capability to query the system for information about important attributes of the items on the parts list. Once the engineer selects the items (bolts, washers, nuts, etc.) to accomplish the fastening function, copies of those items become logically grouped as a fastener.

Tools are now being developed to provide process design support for the production planners including early validation of the design and the process data (including assembly and test processes). The principal use of the 3D product model is to allow the manufacturing representatives to validate the engineering design-for-assembly tools such as those developed by Boothroyd and Dewhurst.

All design actions involving a particular product component are performed using a single object in the database to represent that object; therefore change effects are reflected throughout the system. For example, with power harness cables, the

electrical design, the physical design, and the bill of material are all linked to the same object in the database.

Other changes at the TCF include assigning the team leader responsibility for developing component manufacturing support for the product, prohibiting the engineers who designed a component from assembling the prototype of that component, and requiring all prototypes to be assembled, using the proposed release instructions, by a team which includes representatives from manufacturing. Product design rules emphasize modularity and other characteristics that simplify manufacturing, minimize the difficulty of incorporating changes and improvements, and support tailoring system configurations to meet customer demands. Manufacturing responsibility includes fabrication, assembly, and test.

Results There is greater awareness of shared goals, successes, and problems. Efforts are coordinated more effectively. The resultant reduction in ECs led to a significant reduction in the number of engineers supporting a product after GA. The time from the start of the design cycle to product announcement has been reduced as well. The time from the beginning of design until completion of product engineering support has been greatly reduced. Fewer people were needed for the design; product direct-labor costs were reduced 50 percent, and the process time devoted to customizing products is down by 65 percent.

Remarks Although 3D representations are available, the team has decided *not* to adopt a 3D design product release. Although 2D design information is transmitted to manufacturing via digital release, they believe paper, 2D design drawings will continue to be used on the production floor. Team members said that continued research is needed for solid modeling, data structures, and algorithms for handling very large (20-40 megabyte) models with reasonable interactive response time.

East Fishkill, NY

Product East Fishkill produces common elements (masterslices) and components that become the building blocks for devices, circuits, chips, and the first level of packaging (substrate). A group at East Fishkill provides the requisite electronic design system (EDS) tools for engineers to design customized applications for masterslices and substrates. Other EDS capabilities (software tools) for card, thermal conduction module (TCM), and Clark Board (a board about one meter square with approximately 2000 connections) design are provided to IBM labs world wide by teams from Poughkeepsie and Endicot. East Fishkill provides the physical and logical technology and rules for designing circuits that will become chips and substrates. At East Fishkill, computer-controlled manufacturing lines produce Very Large Scale Integrated (VLSI) logic circuits. In the early 1980s, a "quick turn-around" (QTAT) manufacturing line using more than 100 custom designed tools was put in place. Currently, using a new state-of-the-art facility

and EDS, users can convert an electronic design to a 1500 circuit custom manufactured chip in 5 days. Designers at 25 locations throughout the world use EDS to create design instructions which are sent to East Fishkill (and other sites) where customized chips and substrates (and TCM's and Clark boards) are produced.

Function A team at East Fishkill supports the corporate-wide use of the segment of the EDS that is used for masterslice and substrate customized design. They provide normal system updates twice each year and, if necessary, they can provide very rapid (3 days) modification of the system. EDS supports logic-design capture and verification, test data generation, physical design, and creation of release interface to provide a complete and unambiguous product description to manufacturing.

Much of the design and production process has been automated. IBM has a number of special application programs which operate on the electronic product description to support design synthesis and design verification. There are also application to provide an interface to the manufacturing facilities for semiconductors from chip through system level.

Situation Complexity in digital electronic design at every level from chip to system exceeds the unaided ability of designers to cope with it. The production process involves many steps, each adding cost and value. Design verification relies on software tools and hardware testing; hardware testing alone is not sufficient.

Approach IBM began investigating automated design environments in the 1950s. The architecture for their present system, Electronic Design System (EDS), was defined in 1970. They have a comprehensive set of tools to support both design synthesis and verification. The physical architecture relies on a high performance computer for data storage and detailed computation. A special purpose computer that executes system-level simulations which are compiled from design descriptions is used for simulations of large systems. Workstations, text-only terminals, and intelligent displays are also included.

EDS provides for capture of the logic design and subsequent concurrent physical (placement and routing) and test design. EDS had its own language for design description, but is migrating to EDIF and VHDL. Logic designs are created by engineers using rule libraries. When test and physical designs are complete, they are integrated into a release interface tape (RIT) that contains all the information needed to manufacture and test the product. If all procedures are followed, the RIT can be translated into production instructions within one day.

The logic design is distinct from the technology design. Design synthesis uses rules (that may be technology dependent) which are qualified and certified so that, if a design conforms to all rules, then the RIT is "guaranteed" to produce a functionally correct and manufacturable product. EDS produces a verifiable

design but it is not optimized. Designers generally do not optimize designs by manually "tinkering" with the EDS output. They relax or change the restrictions they had imposed on the system and resubmit the logic design and relaxed rules to EDS which produces a new placement and routing solution.

Design verification is the most time-consuming part of automated design. Simulation, timing verification, and static analysis are used for verification. Hardware simulators, special purpose computers that execute a compiled design description, execute simulations 1,000 times faster than traditional software simulations on a general purpose computer. As a rule-of-thumb, software simulations require 1,000 hours to simulate one second of system operation; hardware simulators do the same in 1 hour. Test vector generation for fault-detection is aided by a policy of using Level Sense Scan Detect (LSSD) design rules. These rules allow designers to overcome the complexity of testing sequential circuits. Virtually 100 percent fault coverage is required for highly complex, dense circuits.

Computer-aided design verification is used to detect over 90 percent of all design errors. Manual inspection and hardware debug are used to detect the rest.

EDS is updated on a routine basis twice each year. If errors are discovered in the rules or if some change is needed, changes can be incorporated and implemented on the production floor in 3 days. EDS is an evolving system, both it and the design process it supports are continually improved as IBM takes advantage of its impressive in-house research capabilities.

Results   When the 3080 was designed, the design process typically required three passes. Today, design is planned for two passes, and the goal is one-pass design. The overall (digital electronic) design cycle has been reduced by 40 percent.

Remarks   Although EDS has been developed internally to satisfy IBM's needs, some laboratories decided to use commercially available CAD tools. Some commercially produced tools are admittedly superior within specialized domains. EDS is migrating to a UNIX™-like operating system. EDS had its own language for design description but is migrating to EDIF and VHDL.

A.3 ITT

Company ITT Corporation

Division All

Location Worldwide

Approach The ITT Corporation formed a small corporate statistical group that researched Japanese management methods, including true statistical process control, Taguchi Quality Engineering including design of experiments, quality function deployment, and multi-function teams. This group spearheaded a corporate-wide effort of advocacy, education, and deployment of these methods. They initiated pilot projects that won support from the CEO.

ITT has a continuing education program using in-house assets from the Statistical Programs Group. The engineer's course consists of two sessions, each of one week length. The first week prepares engineers to apply the methods. They return to their regular jobs after the first session and prepare a project to demonstrate the techniques learned. When they return to the second training session, they present the results of their application to the rest of the class for joint critique.

The training program relies on consultation from Taguchi to develop hands-on experience. ITT estimates that 2 years are needed to train someone to become proficient in the new methods. They do not overly emphasize the theoretical aspect of Taguchi Quality Engineering. The focus is on the practical: they teach tools and their use.

ITT reported that training engineers was not enough. Technology couldn't be used effectively if management philosophy was not supportive. Management came to understand the role of variability in understanding the process. Eventually, both management and the work force had to be re-educated.

A 2 day foundation course teaches the need for new ways of thinking about the customer base, the association of quality and variability reduction, the control of quality, fact-based improvement strategies, the importance of supplier integration, and management/work force relationships.

The cultural change that ITT is attempting to accomplish is difficult to achieve. It has been particularly difficult to get middle management involved in the change. Continuous persuasion by top management, pushing—but not demanding—acceptance of new ideas has been most effective. There have been skeptics, but when convinced, skeptics have also been the most effective proponents of change.

The foundation techniques are the following:

- QFD to focus resources,

- True SPC to manage processes, and

- Taguchi methods to reduce cost, meet schedule, and improve quality.

Product

Situation In 1982, cost analyses showed a 30 percent cost advantage for Japanese automobile manufacturers. Ford Motor Company studied the Japanese management methods and mandated that its suppliers, including ITT, adopt new methods. In response to Ford, ITT started a pilot effort in the automotive group. This effort lasted from 1982 until 1984. Based on the results of the pilot, corporate headquarters decided to expand the trial of new methods to include a mixture of high and low technology and volume applications. Several additional five-month pilots were started. The results were favorable, and ITT formed a small statistics group to promote the new methods throughout the corporation.

Results In the past 3 years, there have been 3000 Taguchi experiments. Ninety per cent of these required no investment, and the results have been improvements of up to 50 percent. There have been no true failures. Statistical process control has led to the reduction and elimination of inspection with attendant improved yields. The design cycle time has been reduced significantly.

These methods do not eliminate the need for skilled engineers, workers, and managers. SPC and Taguchi methods are tools for controlling capital investment.

At ITT Avionics, producibility engineers and design engineers work closely together. In mid-1986 they formed a new design engineering organization to focus on product design and transition to production (this was about the same time the Willoughby templates appeared). In May of 1986 they recognized cultural problem in engineering when trade-offs in performance were needed. Producibility, testability, reliability, and supportability (PTRS) initiatives were defined. Operations and manufacturing formed a producibility organization. Engineering and the producibility group formed a stable team. The team followed a product from design to production by moving from the engineering spaces into the manufacturing area as the product entered production. On one project in early 1987, product engineering transition engineering teams were formed, they initially co-located in the design engineering facility. The PTRS continued, forming a detailed database. The design review process expanded to include manufacturing, quality, logistics—all with veto power. Because people were involved earlier, they did not act as policemen.

Although electronic interconnection among engineers was possible, the team made extensive use of personal interaction. Electronic teleconferencing was used for off-site meetings.

A communications network has been developed to link the design activities. It will include local area networks and high speed data links between sites.

Capture of design rules so they could be incorporated in design tools became a goal. Freezing on tools was not a goal, stabilizing for 3-5 year periods was sufficient. Controlled tool evolution was preferred.

The PTRS design guidelines were coupled with the product engineering/ transition team and the transition time was cut by 20-25 percent from an initial 24 month schedule

Manufacturing has also been expanded to include quick reaction manufacturing (QRM). This activity will also involve the design team. The design team gets experience on the production floor.

Process control is applied on the production floor. Critical parts of the process now have on-line process control data capture and display. Process yields are high. Eliminating or reducing inspection is the goal. ITT Avionics has been selected by a tri-service group to be one of the defense companies attempting to meet stringent DoD 200/WS6536 soldering specification on printed circuit boards, through the use of SPC, thus eliminating the need for 100 percent inspection. Use of SPC has shown a decrease of more than an order of magnitude (4800 to 400) defects per million.

Defect free manufacturing is essential to concurrent engineering and this information is fed back into the design rule base.

Representative samples of Taguchi experiments resulted in:

- $500,000 savings by reducing rejects.
- $125,000 savings on tool costs.
- $1,100,000 annual savings on a solder process.
- 28 percent improvement in power supply product losses.
- $97,000 per year savings in a traveling-wave tube (TWT) process.
- 25 percent reduction in ferrite core bonding production costs.

Other gains from new methods are a 33 percent reduction in the design cycle for an electronic countermeasures (ECM) system.

One study of QFD concluded that FSED could be eliminated, but there are problems getting the voice of the customer.

Source   IDA workshop and site visit

Remarks   ITT Avionics experiences (quite typical for the defense industry) a 5-15 year lag between initial concept development and full production and field deployment. They want to reduce this to 2 years.

The fundamental concepts of concurrent engineering (namely, cooperation, teamwork, trade-off of design features to achieve full life-cycle goals) are not new; they have been used for 30 years or more. The problem has been caused by other factors and pressures resulting in design becoming a differentiated process instead of an integrated one.

A.9 McDonnell Douglas Corporation

Company McDonnell Douglas

Division Aircraft and Astronautics

Location St. Louis, MO

Approach McDonnell Douglas has a corporate renewal program that has been underway since the early 1980s: they make extensive use of automation for information storage and retrieval, design support, logistic support, and manufacturing improvements. They use "natural work groups" (multi-function teams), process control, supplier performance measurement system, flexible manufacturing, computer-aided manufacturing (CIM). They have printed wallet-sized cards with important facts about SPC, Deming, and Juran plus identification of the goals of QFD and Taguchi methods. They are sending people to American Supplier Institute for training.

Product Aerospace, services, and defense products.

Situation There was no mention of the type of severe personal event that motivated many of the other companies. Instead, the corporate renewal program was initiated by the CEO's personal interest in continued corporate excellence. More recently, initiatives from DoD customers such as the *Transition to Production* (templates) and *R&M 2000* provided additional motivation for concurrent engineering.

Results McDonnell Douglas compiled a report of significant improvements during 1987.[66] Some of the results are reported below:

Automation Improvements

- TAV-8B Graphics Development Fixture completed 18 months faster than AV-8B. This savings was the result of using an electronic mock-up. After 30 months, changes per Cumulative Drawings reduced by over 2/3 on TAV-8B compared to AV-8B. Improved engineering quality is the result of coordination possible with the electronic development fixture and working with computer-aided design tools. GR MK.5 Nosecone produced 5 months earlier than original schedule also as a result of using an electronic development fixture. T-45 (at Douglas) using the electronic development fixture and continuous checking of all releases against the electronic mock-up and had approximately 80 percent fewer changes as compared to paper drawings.

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66. (Point of contact Susan Stitch E120/107/3/C1/233-0247.)

- Preliminary design for high-speed vehicles in 8 hours instead of 45 weeks using a manual process.

- Reduced time to prepare the Approved Source/Quality Verified Product List for NAVAIR from 511 hours to 148 hours.

- Saved 50 percent in creating over 500 drawings for the Nuclear Technology Program.

- Reduced depot turn-around time by 6-8 weeks by eliminating paperwork in a system for customer initiated trouble reports.

- Automated "Modular Power Subsystem Program" (NASA contract) testing and saved $357K net. Parts traceability program saved $69K/year on the same effort.

- Consolidated Company Policies (CP) and Standard Practices (SP) reducing CP's by 51 percent and SP's by 2.5 percent. The consolidated system was brought on-line.

- Developed front-end for structural analysis program (NASTRAN) that allows savings of 98 percent in preparing the data for structural analyses.

- Use digital data according to the CALS concept is reducing costs 25 to 30 percent and cycle time 20 to 25 percent in comparison to manual design and documentation systems.

- The automated composition system (ACS) when completely implemented will eliminate the need for 64 production support people and reduced production cycle time for document preparation and publication by a significant amount.

- Support asset management system (SAMS) spares ordering through delivery reduced the need for 30 people in supply support department. (There are additional savings in other divisions.)

- Computer-aided technical illustrations (CATI) for technical manuals when completely implemented will reduce illustration preparation times by 2/3.

Teleconferencing Saved $400K in travel costs on the Tomahawk Program by using teleconferencing.

Process Control Use of Applied Process Control on the Tomahawk Production facility resulted in reduced failure rate for wire harnesses at the AUR level from .85 percent in 1985 to .21 percent in 1987 (3Q). Material Review Records per parts completed, reduced from 11.7 percent in Jan 87 to 1.4 percent in September 1987.

Manufacturing Control System Improved management methods reduced paper costs by 50 percent on two manufacturing reports.

Subcontract Natural Work Groups $5.4M annual savings on Tomahawk, 30 percent reduction in subcontract management work force, 73 percent reduction in paid overtime, 20 percent reduction in hardware discrepancies.

Hidden Factory Costs Scrap and rework cost reduction efforts—compared to 1986—reduced rework costs by 29 percent, scrap costs by 58 percent, and non-conformances by 38 percent.

Procedural Improvements Improved system for processing Design Change Notices (DCN's) saved 34 percent of the time to process a DCN, using natural work group suggestion for improvements to the Process Specification System will save approximately 2000 manhours per year.

Expert System Using an expert system and participation by reliability and maintainability specialists for reliability and maintainability trade-offs during conceptual design gave improved producibility, reduced development cost, and reduced life-cycle cost. Potential savings of operation and support costs—60 percent. The effort was *not* any more expensive than traditional methods.

Other Gains

- Concurrent engineering (integration of reliability, maintainability, producibility, and Integrated Logistics Support (ILS) with design on-project) resulted in the F/A-18 Hornet, which is demonstrating twice the reliability and 1/2 the maintenance in the fleet compared to its predecessors, the F-4 and the A-7.

- Weld yield improved by 300 percent, defects per unit decreased by 70 percent, reduced set-up time.

- One-of-a-kind reactor project using CAD system reduced bid price by 60 percent, schedule by 18 percent, 68 percent fewer changes, reduced scrap by 87 percent.

- High speed vehicle trade study using synthesis technology in less than 1 percent of the time for manual effort.

- Applied Taguchi methods to IR problem and reduced schedule by 83 percent

Source Site visit, briefings at the workshops and data provided by McDonnell Douglas.

Remarks McDonnell Aircraft Company developed a software package (MAS) under a contract to Wright Field which provides an in-memory repository for digital models and a means of data manipulation to support CAD/CAM translation.

They have also developed another concept called "parametric evaluation" that allows them to store and integrate surface and curve digital representations created in any other CAD system. They use it for extracting the necessary properties from Northrop's NCAD system, Dassault's CATIA system, and from their own curve creation system. It allows manufacturers to access the *original data definition*. They believe that MAS and parametric evaluation are important elements in enabling data transfer and product information exchange.

A.10 Northrop Corporation

Company   Northrop Corporation

Division   Several

Location   Various

Situation   Northrop seeks to achieve continuous improvement in the productivity of its operations and the quality of its products. Database management has become an increasingly important part of this process as projects become more complex and as staffs are more dispersed. Decades ago, all the people who were involved in designing an airplane could work together in one room. Since then, increasingly demanding and complex requirements have caused enormous growth in design teams and resulted in increasing specialization—and physical separation and dispersion of the design team. One of the objectives of managing a complex project with a dispersed staff is assuring the use of a common database. No one should be wasting time or material because of late or outdated information.

Previous processes of design, manufacture, and support were essentially manual and slow in responding to changes. Information was passed manually on paper between major departments, and this process allowed error to propagate through the data. Even with the best drawing and checking systems, design flaws have existed on every weapon system, and remained until confronted in manufacturing, lab and field test, and, worst of all, after deployment. The later in the process that flaws were detected, the higher the costs of correction. Many flaws and errors would cost so much to correct that they are left uncorrected—with accumulated major adverse impact on R&M, readiness, and life-cycle cost.

With all the dispersion of the design teams, they still can and must obtain the benefits of integrating all the various life cycle requirements into the initial design. Recent advances in computer technology enable Northrop to do that by bringing everyone back together under one roof, electronically.

Approach   Northrop's approaches to achieving continued improvement in quality and productivity have included three important thrusts: electronic product definition, phased parallel release, and statistical process control. The first two of these had to be developed in house to ensure timely availability to meet the needs of company programs.

Electronic product definition consists essentially of developing a computer database with all the information needed to build and support a product. There are several advantages to such an approach, e.g., extreme accuracy, but perhaps the most important advantage is the reduction in errors and wasted effort. This is brought about by having a single, integrated database so that everyone—designers, manufacturing engineers, logisticians, etc.—can work with a common database from the beginning. Because this database is being updated continually,

the latest version is available almost immediately to all users.

The object of phased parallel release is to introduce considerations of manufacturing, material, quality and logistics support into the front end of the design process, along with engineering. Representatives of these disciplines, collectively and in parallel as members of the product definition team, develop, exchange, investigate and completely define the data required to produce and support the desired product. This collective effort creates an environment enabling continuous improvement of the processes involved in developing and maintaining a weapon system.

Results

Example 1

Through the parallel release meetings, it was realized that the manner in which bulkhead designs were being prepared could be streamlined. It was noted that before implementing parallel release, the standard approach to preparing bulkhead designs was to prepare an assembly design and a wire frame model. After reviewing this approach it was decided that these two activities could be combined into one detail activity design. This change in design methodology, combined with applying the parallel release approach throughout the product definition process, resulted in a total reduction in bulkhead design time from approximately 13 weeks to 6 weeks. The overall average savings for direct and indirect organizations totaled approximately 30 percent.

Example 2

All of Northrop's manufacturing divisions have used statistical process controls, in some cases routinely for decades. We have found them to be essential tools with significant payoffs in improving the yields of company processes, as well as improving the quality of the material we procure from subcontractors and vendors. One division achieved a 41 percent improvement in the quality of material procured from subcontractors and vendors over the past several years, and they project a further improvement of 47 percent.

Statistical Process Control (SPC) Taguchi techniques for process improvements are now being formally taught to Northrop engineers in several divisions, and we expect significant expansion of the use of these techniques in routine development and stabilization of certain types of manufacturing processes.

The benefits derived thus far from examination of statistical process control, Taguchi methodology and quality function development have been integral to the prime objective of increasing quality at least cost to both customer and contractor. Northrop implemented variability reduction

program (VRP) techniques in commercial and military projects. Special emphasis is being directed to advanced aircraft and missile programs.

The following are some examples of benefits realized to date at Northrop Aircraft Division:

- In central fabrication Northrop applied SPC to a aluminum quench oven operations. The automation provides precise data acquisition and immediate access and control of all phases of the process.

- SPC application in a new lubrication system precludes heat build-up and increases tool life. In stretch forming, disc sanding, and drilling, a 50 percent quality improvement has been realized.

- An automated machine tool cleaning process with SPC eliminates debris and defects on cutters, resulting in production of conforming machined parts.

- Several SPC pilot projects are currently in operation at the Aircraft Division. They include boring mill operations for side-brace and wing attach holes, fuselage center section skin preparation and composites.

Example 3

To reduce the variabilities associated with the design and manufacture of advanced ECM equipment, Northrop's Defense Systems Division (DSD) is employing techniques ranging from integrated computer aided design/computer aided manufacturing (CAD/CAM) systems to SPC techniques.

These projects fit an integrated manufacturing strategy which is to integrate proven flexible manufacturing systems for small lot size and frequent design changes. The division's systems approach has been developed in line with the Air Force's integrated computer aided manufacturing approach of top-down planning and bottom up implementation.

Computerized models develop system requirements and aid the process of defining appropriate architectures and circuit elements to satisfy customer requirements with reduced design variability. Other models are preprogrammed with detailed design rules (piece part derating, part tolerances, part parametrics, etc.) to prevent, at the earliest possible stage, design variations that would affect not only first time success but design, build and performance repeatability.

The major thrusts of DSD's efforts include:

- A new CAD/CAM system in place to provide automated work instructions to the factory floor. This integrated computer system standardizes the format for process documentation in manufacturing

engineering. The combined test and color graphics of work instructions are validated for accuracy and configuration control and then sent to the factory floor terminals. Operators use this paperless system to build avionics equipment.

- Paperless systems incorporating bar coding and on-line computer reporting are being introduced to the factory floor. The data collected at the cell controller level are the basis of our SPC plan. The systems reduce variations in data collection and reporting through improved data integrity. Only validated and current information is made available for production materials processing.

Example 4

Studies showed that implementation of a product definition enabling technology could reduce engineering change activity as well as change activities in the areas of NC part and tool programming, tool design, tool fabrication planning, and material ordering. After analyzing reductions associated with the direct change activity, other support organizations realized indirect savings in the operation of their functions. Examples of savings include 16 percent in part and tool fabrication planning, and 24 percent in configuration management.

Example 5

The major benefits of electronic product definition include 100 percent change incorporation, the ability to make changes more quickly, increased precision, better first fits of structure, tubing and wiring, simplification or elimination of mock-ups, faster numerical controlled machine programming, etc. Electronic product definition has resulted in a 40 percent reduction in the time required for NC programming on a control surface. It has also decreased, for example, the defect rates on tubing fit in manufacturing from as high as 40 percent to 3 percent, a 13 to 1 improvement.

Summary Phased parallel release, electronic product definition and, statistical process control are being applied on several Northrop programs. As a result of the major benefits already achieved, Northrop is working to enhance these and other concurrent engineering processes and extend them to additional programs and products. Through these and similar processes, Northrop is committed to continued use, and expansion of, concurrent engineering concepts and tools to achieve continuous improvement in productivity and quality.

A.11 Texas Instruments

Company   Texas Instruments

Division   Defense Systems & Electronics Group, Plano, Texas. Provides electronic systems for classified and unclassified weapons system programs. System integrator for HARM missile and other systems.

Situation   Texas Instruments has been pursuing a strategy that integrates design and manufacturing automation, quality and producibility objectives. The drivers are the need for competitiveness, cost reduction, and customer satisfaction.

Approach   Texas Instruments reported eight initiatives that are closely related.

- Their quality and reliability assurance function has progressed from traditional inspection as a means of separating good parts from bad to a system of control to ensure the stability of the process. They now use Statistical Process Control (SPC), quality improvement teams, and work with their suppliers to improve the quality of incoming parts.

- They instituted an *education* program consisting of sending 800 managers to Phil Crosby's course in Florida. These managers monitor in-house courses based on the Juran Tapes to all exempt employees. Five years later, they started a series on Taguchi methods using both American Supplier Institute (ASI) and internal sources. They are familiar with the concepts of Quality Function Deployment but recognize the difficulty discerning the DoD customer's requirements. They supported The University of Texas at Arlington in developing a graduate course in Design for Quality and Producibility in response to the Willoughby initiatives as one example of their academic involvement.

- They expanded their instituted policy of providing representatives from engineering specialty areas to include Producibility and Testability with the already established disciplines of Reliability, Maintainability, etc. as part of the Product Design Team. These members perform three functions: conclusive advice regarding their functional specialty, education for other design-team members about their functional specialty, and automated tool design for computer-based tools to assist in performing design support related to their functional specialty.

- They have internal R&D initiatives to provide automation support for integrated engineering. Their strategy and well-developed plan have been in place for some time.

- They have implemented a master parts library and an integrated personal workstation to support concurrent design.

- They have invested, and will continue to invest, in improved hardware for production and test so as to be able to include advanced technology such as surface-mount technologies in their designs.

- Expert system for many design support functions are being developed.

- The JTAG boundary-scan design architecture is being adopted and Texas Instruments will include hierarchical testing as a design concept.

Results   The cost of quality programs has decreased significantly. Exact data is proprietary, but the relative improvement is about 80 percent. There have been improvements in purchased parts (39 percent), number of changes in microwave modules (75 percent), and metal fabrication prices (72 percent). The incorporation of Design for Producibility engineers saved $3,000,000 in one program over the first three production lots. There have been reductions in engineering change notices (ECN's) per drawing (estimated 1/drawing) and an 8:1 improvement in analysis time for producibility time for producibility evaluation of printed circuit boards and components through the use of a local automated Component Analysis System (CAS). Based on MIL-STD-275E, CAS is a fully integrated analysis program and component database containing physical dimensions, producibility, and layout/shape code data on 25,000 part numbers. It has been used on 1,000 analyses. There is a goal of reducing design time for the advanced microelectronics packaging cycle from the present 25 weeks to 19 weeks in 1990 through application of system integration techniques, including in-circuit test integration, part data load, factory interface, and data control.

Remarks

Regulations and Specifications It is estimated that redundant or unnecessary government quality regulations and audits add significantly to the cost of quality engineering at TI. In one example the flow-down of first and second level specifications from one contractually referenced source was 1,300 specifications whose average age was 11 years.

Requirements Difficulty in establishing a dialogue concerning requirements (voice of the customer) is the principal reason QFD is not used more in TI.

Opinions on Technology The mere existence of design automation tools does not mean that useful results will occur. There needs to be a design automation methodology along with the toolset in order to achieve the potential of the toolset capability.

Miscellaneous

- Premature drawing release often results from unrealistic contract schedules or late changes in system requirements.

- TI has a family of design guides including 12 producibility guides and 7 checklists.

- Wave soldering is a topic that is drawing a lot of attention. Texas Instruments is participating in a Tri-Service effort to eliminate 100 percent inspection requirements from DOD-STD-2000.

- Surface mount technology is not incorporated into more designs because engineers perceive it as risky based on cost and capability delta as more conventional methods remain competitive.

B. METHODS AND TECHNOLOGY

The methods and technologies of concurrent engineering are described in this appendix. The level of detail of the presentation is intended to provide an introduction to the concepts. The discussion follows the format established in the body of the report: engineering process initiatives, computer support improvements, and formal methods.

Informative in nature, this appendix is not a recommended plan for the DoD or for any particular company. Each company should be free to develop its own plan for improving their product development, production, and support processes. As a customer, the DoD's primary concern is that the plan provide systems in less time, at lower cost, and of higher quality. These are ways that other companies have achieved these goals.

B.1 Engineering Process Initiatives

The first requirement for achieving success in concurrent engineering is support of management. Concurrent engineering involves the integration of contributions from diverse specialists. Where it has been successful, much of the credit is attributed to the involvement of senior management in establishing the goals of improved quality, cost and schedule; in forming the teams of qualified people; and in providing the teams with the necessary tools.

B.1.1 Multifunction Teams

Multifunction teams are one method of facilitating the optimization of all important measures of a product's function—performance, producibility, ease of maintenance, reliability, cost, and quality. Management forms a team of members who have specialized knowledge in different portions of a product's life cycle to concurrently engineer both the product and the downstream processes for production and support. Involvement of these people in the design, particularly in the early stages, has been shown to reduce the time for total product realization. For example, the participation of representatives of the manufacturing or production branch has resulted in designs that can be produced with fewer modifications. In one company, even the prototypes are produced by the production facility, not by a prototype shop.

Formation of the multifunction teams varies among different companies. Some organizations form process-oriented multifunction teams, and others product-oriented multifunction teams. Membership on the teams may remain fixed or it may vary over the life of a product. Teams are usually co-located, but the location can change as a product moves from design to production. Because personal communication is such an important feature of this method, the teams are usually small (fewer than 12 people). Multifunction teams have been used on weapons systems for at least the last 15 years.[67]

In one case, [Seifert [1]] teamwork was evaluated by the participants as being the most important factor in one large company's successful productivity improvement program. In some organizations, team members who represent production divisions are selected directly

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67. Multifunction task teams were used to design the F-15.

from those divisions. Other companies have created a new specialist, the producibility engineer who participates with the design team. One company using such a specialist said that communication skills were one of the most important qualities for a person to be considered for such a position. A common observation is that use of multifunction teams improves the ability of designers to create subsequent designs that incorporate from the start features reflecting down-stream considerations.

B.1.2 Design Documentation Management

This section provides a description of the method of design documentation management and its relation to concurrent engineering. Design documentation management refers to the procedures used to specify how designs are created, analyzed, verified, modified, and approved. Design documentation management is a necessity for any design effort, but with concurrent engineering it becomes more challenging. Because concurrent engineering allows people who have a functional specialty other than traditional design to participate in the design process, it must also allow them to have access to the collection of information called the design.

A design is created and refined over some interval. The process of creating a design and recording it as the design includes some amount of trial-and-error experimentation. Different alternatives are tried and discarded until a solution is achieved. The challenge of design documentation management is that the process must allow freedom for the engineer to try new alternatives while maintaining control of who is allowed to alter the design and when they are allowed to do so. It also concerns procedures to select one version of the the several options that are being evaluated and to designate it as the design. During concurrent engineering, design documentation management must resolve the tension between allowing team members to have access to the several alternatives versions of the design so that they can evaluate its features with respect to their special concerns and the need to avoid generating excess work by members who may be evaluating alternatives that will only be discarded at a later stage.

Design documentation management is included as a method, not as a technology, because it is needed independently of whether the design process is automated. If the design process is automated and the design is maintained in a CAD/CAE database, then there will be a requirement for a technology to implement the techniques of documentation management. In any event, the method described here must include a specification of procedures to be followed by the individuals who are participants in the design process.

B.1.3 Tracking the Requirements

This section provides a description of the methods used to associate weapon system (product) and process features with the requirements (the customer's voice). We sketch the issues and briefly describe one systematic technique of capturing the requirement and mapping it into the early design.

Implicit in the preceding discussion on methods to measure, design, optimize, form teams, and manage the data is the assumption that the developer understands what is needed—the requirement. In practice this assumption is not always satisfied. For weapon system development, in particular, the "customer" has many diverse interests. Procurement

agencies, operating commands, support organizations, and research facilities all have slightly different objectives. Although various acquisition reform initiatives may attempt to improve the ability of these diverse communities to reach consensus of the common goal, the methods discussed here assume that the process is operating in the existing mode.

The first requirement is to capture the "voice of the customer" (VOC) in terms that the engineer can understand. This is not the same as translating the engineer's concept of the need into a presentation intended to arouse the customer's desire for a better system. During the several workshops that were part of this task, participants clearly voiced the opinion that capturing the VOC is both necessary and difficult.

Multifunction teams may be used to capture the VOC, but representatives of marketing will usually take the lead role. Although surveys may be used at this stage, evidence exists that surveys may capture information that is somehow biased. The "Blue Two" program sponsored by the Air Force allows engineers to spend time in the field performing maintenance on fielded systems. Several companies that participated in this program report that it is an excellent vehicle for communicating some of the user's needs to the engineer. At least one company is conducting supportability awareness training for designers who must perform maintenance tasks while wearing chemical warfare protective suits.

One formal technique for capturing the user's requirements and mapping them into product and process parameters is called quality function deployment. Quality function deployment, or QFD, originated in Japan and has been practiced there since the mid-1970s. It consists of techniques for creating and completing a series of matrices showing the association between specific features of a product and statements representing the VOC. It is taught in several versions, notably Macabe's four matrices showing product planning, part deployment, process planning, and production planning; Fukahara's House of Quality approach; and Akao's matrix of matrices. [King [4]]

QFD uses teamwork and creative "brainstorming" as well as market research to identify customer demands and design parameters. The correlation between the demands and the design parameters is ranked and normalized. Parameters of competitor's products are also identified and ranked. The top-down design process continues as functions, mechanisms, failure modes, parts and subassemblies, new concepts, and critical manufacturing steps are identified and traced to critical customer demands and competitor's products. Matrices are a means of recording the information to show correlations. If the customer demands are the rows of a matrix and product features are the columns, it is possible to show positive and negative correlations among the product features in a triangular table above the matrix. The triangular table, atop the matrix resembles a roof, hence the term "house of quality".

In the United States, QFD techniques are taught by several organizations including the American Supplier Institute (ASI) and GOAL/QPC. The House of Quality technique is more widely known among U.S. companies. [Hauser [2], Sullivan [3]] One of the reported advantages of using QFD is that it reduces changes as a design enters production and it decreases the time needed to get a design into production. In one widely reported case, [Hauser [2]] a Japanese automaker using QFD was able to reduce start-up costs by 20 percent in 1977, by 38 percent in 1978, and by 61 percent in 1984 when compared to their experience before they began using QFD. One of Toyota's suppliers reduced the number of engineering

changes during production deployment by more than half.

Some U.S. companies have developed their own techniques for establishing the requirement and translating it into product features. Responding to the strong guidance contained in R&M 2000, McDonnell Douglas Astronautics recently formed a multifunction task team for the SRAM II competition. Using locally derived natural work groups they translated reliability and maintainability requirements (topics that had been traditionally viewed by many engineers as "emotional issues") into identifiable and measurable design characteristics.[68] At least one company is reported to have created a special facility where potential customers can validate their requirements in a system that is designed to capture and compare needs independently of the rank or seniority of the proponent of a particular statement.

Both QFD and *ad hoc* techniques are being used. Companies that use QFD in the U.S. are gaining experience by progressively applying that technique to more complex design problems, i.e., part, assembly, subsystem and system designs. Although QFD appears to offer substantial benefits in the design of complex systems such as military systems, the application of QFD to such tasks has not been publically reported. Whether QFD can be applied to such systems is an issue to be resolved.

B.1.4 Process Design

This section presents methods of designing and deploying a process. Each company contacted has historically defined various steps to be performed in the production process. The detailed description of the production process can be traced [King [4]] to Frederick Taylor's studies of manufacturing in the early 1900s. Engineers, particularly industrial engineers, designed procedures used in manufacturing processes. Once these procedures were translated into steps that the supervisors and workers could understand, the task of managing and improving the process became feasible. In many successful organizations manufacturing processes are described using what Deming calls "operational definitions". Operational definitions tell the workers what is to be done in unambiguous terms that provide a way to verify whether or not the procedure is correctly followed.

The adoption of formally specified steps for the design process has been a more recent development. Design process has been more difficult to describe. Not only do design methods vary among companies, they also differ between different divisions in the same company. Because design has been perceived as an inherently creative process, there has also been some resistance among practitioners to reducing the process to anything that might resemble an automatic procedure. In some instances there is insufficient knowledge and tools for manufacturing design, lack of accurate data on field failure modes, and inadequate performance models of the product and production systems. [Whitney [5]] Although tools to support product design synthesis and analysis (at least parts thereof) are available, describing a process to concurrently design the product and its production process (much less

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68. "The McDonnell Douglas Concurrent Design Experience, A White Paper," prepared by the McDonnell Douglas Astronautics Company, St. Louis Division, identification code 2604D, p. 5.

its support system) is a formidable challenge.

Despite the obstacles, both government and industry have made progress in discovering better design methods. The DoD and the Services have provided some guidance in *DoD 4245 7-M, Transition from Development to Production, NAVSO P-6071 Best Practices*, and R&M 2000. The research community has several initiatives (e.g., Merchant [6] , and DARPA [7]) for improving productivity and many of these are concerned with the problem of improving the design process. The Strategic Approach to Product Design [Whitney [5]] and various company initiatives both to implement the "Best Practices" and to improve on exiting procedures are further examples of efforts in this area.

One company's experience, as presented to a workshop, was particularly informative. They discovered that although a written procedure for system design was available, adherence to the written procedure was so inconsistent as to make improving the written procedure an impractical task. Instead, upon deciding the best way to accomplish the design, they recorded the new procedure as their baseline. Incidently, they are pleased with the new procedures.

AT&T developed [Ackerman [8]] a set of simple management guidelines, Process Quality Management and Improvement (PQMI), to simplify the task of organizing the improvement activities. Central to the PQMI guidelines is understanding one's own process, customers, suppliers, and the related inputs and outputs (see figure B.2). The guidelines show how a variety of common techniques, such as block diagram, cause and effect diagram, control charts, and Pareto diagram, can be used for defining the processes, the inputs and outputs.

AT&T has applied the PQMI guidelines in a variety of "white-collar" processes, such as voucher processing, billing, accounting, and management of hardware and software development projects. The structured approach of PQMI has led to reduced "fire fighting". clarification of work priorities, and prevention of problems.[69]

The PQMI guidelines include a seven-step process and list the tools and techniques that have been found to be most useful at each step. The seven steps are:

1.   Establish process management responsibilities.

2.   Define process and identify customer requirements.

3.   Define and establish measures.

4.   Assess conformance to customer requirements.

5.   Investigate process to identify improvement opportunities.

6.   Rank improvement opportunities and set objectives.

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69. We are indebted to Madhav Phadke for this information. "Fire fighting" is AT&T's term for crisis management.

7. Improve process quality.

There is considerable divergence among companies regarding how they describe their design process, but the companies reporting success in concurrent engineering have made a conscious effort to examine their process, to establish a measure of its effectiveness, and to convince at least some of the key people to continue to improve that process. All of these companies are practicing at least some of Deming's 14 points. [Deming[13]]

An issue concerning the process design is the degree to which the DoD, in pursuit of legitimate concerns about poorly designed or controlled processes, should specify how a contractor should design and control its internal processes. The consensus of experienced individuals both in DoD and industry is for DoD to avoid specifying *how* and improve its ability to define *what* is needed.

B.2 Computer and Other Technology Support

This section contains information about technologies that are associated with concurrent engineering. Although several companies were very clear in saying that new technology is not needed to practice concurrent engineering (or to achieve the fourfold goals), this section focuses on two classes of technological improvements: those associated with information and communication, and the class of technologies that called production technology. These technologies may already exist but with less than desired capability, or they may be research topics. Concurrent engineering isn't dependent on their deployment. Their development and deployment will, however, promote more rapid acceptance of concurrent engineering and will improve the efficiency with which it is practiced.

B.2.1 Information Management and Communication

The first class of technology includes the means to capture, represent, present, manipulate, and integrate information about the product design and the design of the process used to produce it. It may include information about the process used to design both the product and the process. This class also includes technology needed to deploy the information to the design team member's workplace.

B.2.1.1 Information Capture

Information-capture technology includes software and hardware that the designer uses to represent the original design concept and all its derivatives. It includes the means of capturing information about the process used to produce a product, information about design rules, and information about downstream effects of various design alternatives. It also includes the technology needed to filter and condition the data that produces this information.

Information capture technology has been recognized [NCMS[9], Merchant[6]] as a high priority research topic.[70] At least one of the companies that participated in the workshops

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70. Sensor-based control of manufacturing equipment and process was ranked as the highest priority research topic at the March 11-12, 1987 National Science Foundation Workshop.

believes the development of lessons learned databases is one of the most important improvements needed for concurrent engineering.

Information capture includes real-time capture of information by sensors as part of measuring process capability and also off-line data capture. After raw data has been collected, it must be filtered and conditioned to be useful for many decision processes. Techniques of filtering data so as to create a knowledge base are research topics.

A current example of information capture software is the Design for Assembly Toolkit by Boothroyd Dewhurst, Inc. This software system is used to capture the structure of a new product concept in order to assess the possibilities for part count reduction and to identify future problems in assembly processes.

B.2.1.2 Information Representation

After information has been captured and filtered it must be stored in a form that permits it to be used by a variety of software tools and on a number of different hardware devices. Standards for representing data support this capability. Among the types of standards that have been helpful for data representation are such well-known standards as the ASCII character codes, standards for designing devices such as the JTAG boundary scan or LSSD, and standards for representing data that are exchanged such as ASN.1.

Additional work is needed to develop common standards for representing engineering information. Several workshop participants described the DoD Computer-aided Acquisition and Logistics Support (CALS) initiative and the Product Data Exchange Specification (PDES) effort as very promising programs in this area. Standardization efforts are also being conducted among international bodies, for example ISO TC184/SC4/WG1 (International Standards Organization Technical Committee 184, Subcommittee 4, Working Group 1) is developing a tolerance model. Their July 1987 working paper (Document 3.1.1.6) notes that as communication of product definition data comes to rely on digital communication instead of engineering drawings, the importance of providing unambiguous digital models increases.

Closely related to standards for representing, but at a slightly more abstract level, the concept of modeling provides a technique for supplying semantic meaning for an item of information. Models of products and processes may be represented as conceptual schema, or they may appear as mathematical expressions. Accurate models promote understanding of the process and simplify creation of integrated systems. Creation of information models is more difficult than defining two-way exchange standards between systems that already share the same information model. Consequently, many researchers consider it to be an essential first step.

B.2.1.3 Presentation

After information has been captured, assuming it can be represented in a useful form, it must be presented to the members of the design team in a clear format. Presentation technologies include graphic displays and their software, 3-D and solid modeling languages, color displays, paper, and teleconference facilities. They also include standards that support development of distributed and transportable presentation packages. The X Window [Scheifler [10]] system is gaining acceptance as a standard for a window system that can be implemented on different computer systems in a network. It allows applications programs to

develop a common interface to windows throughout the network.

Teleconferencing has also been used to support the presentation of information to geographically distributed members of a design team. One company that has used teleconferencing is pleased with the results but they do not believe teleconferencing will eliminate the need for face-to-face meetings.

Effective presentation must also extend to hard copy printouts of design or process analyses. In some cases, paper or simple voice communication can be more effective than electronic transfer. One large manufacturer reported that although electronic transfer of design data to the factory was possible, paper was used because it was easier for the people who had to use the information.

One software package[71] produces a structured print-out of the product design, illustrating the relationship between final assembly, subassemblies, sub-subassemblies, etc. The structure forms the basis for illustrating the distribution of assembly and manufacturing costs and also for identifying possibilities for product simplification.

B.2.1.4 Manipulation

The design process requires more than just capturing, storing, and retrieving information; it requires that some value should be added to the information. The value added may take the form of design synthesis, functional decomposition, or analysis of design objects. During concurrent engineering, the value also includes creation of models of the downstream processes that produce and support the product. The ability to simulate complex downstream processes remains a limitation to full concurrent engineering in some domains.

The procedure for adding value to design objects involves manipulation of the object. The manipulation can take several forms:

— finite element modeling to assess the behavior of the object;

— continuous fluid dynamics for evaluating the interaction of an object with a fluid environment;

— discrete event simulation or application of heuristics to predict partially understood implications of design options;

— some simple translation of data.
In any case, the manipulation is usually performed on some computer, using design support software.

Concurrent engineering is implemented more easily when the manipulation routines are easily used, computationally efficient, and accurate. The information that the routines provide should be presented in a form that the design team can easily use.

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71. Design for assembly software.

Manipulation technologies are being advanced rapidly, but individual software routines are not always developed in such a way that they work together. The next section addresses the technology associated with ensuring that manipulation and other computer technologies are integrated so as to support concurrent engineering.

B.2.2 Integrating Technologies

Concurrent engineering teams up specialists who typically address designs using their own methods, representations, and manual and automated tools. Given the trend toward the use of automation for synthesis, analysis, and capture of designs, multifunction design teams will require tools and representations that work together easily. Integrating technologies are aimed at reducing the cost of evolvable, tailorable tool interoperability. At the same time, they have the possibility of drastically reducing the DoD cost of receiving and maintaining engineering data. While this is an extremely important issue for DoD, it is a secondary issue from the point of view of concurrent engineering.

Within the class of integrating technologies, two are of great importance: environment frameworks and description languages. The first holds the possibility of enabling a process of evolvable, tailorable, and universal automated tool integration. The second holds the possibility of standardized, automated communication of product designs.

B.2.2.1 Environment Framework Development and Standardization

In several meetings of groups concerned with the technological aspects of concurrent engineering, the groups clearly indicated that engineering environment frameworks are a significant facilitating technology for concurrent engineering. This agrees with the team member's experience on the subject.

An engineering environment framework is a response to the fact that as design complexity increases, the use of automated tools increases, but that as the use of automated tools increases, complexity is added to the engineering process. Thus an effort to manage complexity of designs increases complexity of the engineering process. This point is exacerbated when designs are decomposed and addressed in highly interrelated subtasks or when specialists are required to address various aspects of a design. Such an approach requires the following characteristics and requirements:

- integrating and accessing automated tools easily;

- controlled sharing of design information;

- tracking of design information;

- tracking of design dependencies and changes, and propagation of their effects; and

- monitoring of the design process.

These are characteristics and requirements that increase as the use of concurrent engineering increases. The fact that teams are usually geographically distributed makes this problem even worse because information sharing and control, process control, and perhaps even tool integration and access must occur over long distances.

To respond to these requirements, a framework is needed for tool integration based on information sharing. It should offer a standard, extensible set of services and interfaces to be used by applications. It should control and allocate data resources, provide concurrency controls, archiving, and a query capability.

The basic functions of an engineering environment framework that would support concurrent engineering are:

- tool integration—the ability to operate, efficiently and uniformly, tools with different data and hardware requirements;

- data exchange—the ability to translate and to communicate data among different hosts and tools not only withing the the environment but also between the environment and external systems;

- engineering and manufacturing management and control—the facilities to monitor the design and manufacturing process and to impose automatic and manual controls on accessing and modifying data;

- information management—the facilities to describe and to control globally available environment data including the creation and manipulation of data, the imposition of data validity and constraint checking, version and configuration management, concurrent transaction control, and backup and archive management; and

- environment administration—the tools and specifications for managing the data dictionary, tools, workstations, user profiles, and control rules.

It is important to understand that the DoD needs standardization of such environment frameworks at the service and specification level. DoD does not require, and should avoid, standardization at the implementation level. The standards must offer a means for tailoring to meet the requirements of a large number of different organizations. They must be able to evolve to meet the challenges of new design processes and tools. They must be implementable to create environment instances that function efficiently on distributed, heterogeneous platforms. The specifications and services must be implementable with reasonable efficiency on many different kinds of hosts. [Linn and Winner[11]]

There are several government and industry engineering environment framework activities. Unfortunately they are not proceeding from a common vision. This would be acceptable if these efforts were intended as research. The basic environment is no longer a research issue. If the drive toward standards is to occur based on these efforts, a greater commonality of vision will have to be reached.

B.2.2.2 Description of Engineering Designs and Characteristics

Some of the participants in this study assert that a necessary requirement for concurrent engineering is the ability to represent the object being designed in an accurate, unambiguous language. In addition, moving from total reliance on design drawings to electronic representations that can be accessed by many team members is an important advance in design technology that allows teams to be more productive and provides an opportunity for concurrent, integrated execution of different design tasks. Other participants point to the existence of successful concurrent engineering efforts of many kinds and infer that a common

unambiguous representation of the design object is not necessary. It seems clear that such a representation or family of representations is desirable. DoD, through the CALS initiative, participates in the effort to develop such a representation and foster its implementation.

There exists now a national effort to develop such a specification.[72] There is a national voluntary group, supported by the CALS initiative, whose goal is to develop Product Data Exchange Specification (PDES). An industrial cooperative has formed to accelerate implementation of the technology.

The PDES endeavor supports industrial automation in its broadest sense. The resulting standards would deal with the entire range of product data and is intended to represent the US position internationally in the quest for a single standard for product data. The term product data denotes the totality of data elements which completely define a product for all applications over the product's expected life cycle. The data include not only the geometry, but tolerances, material properties, surface finishes, and other attributes and features that completely define a component part or an assembly of parts.

PDES must provide the capability of exchanging data among the multiple computing systems that will be involved in the product life. There is a particular necessity for archived models that will be interpreted at a future date by an unknown system. Industry has found that the ability to exchange product data among a variety of different vendor computer systems is critical to its external relationships with contractors and customers.

It is important to understand that the conceptual schema of the PDES model, while built to support application areas, is supposed to be independent of both the physical implementation and the applications making use of the information. The PDES model is referred to as the Integrated Product Data Model (IPDM).

The plan of the volunteer group is that PDES will be developed incrementally. For PDES version 1.0, the intended scope encompasses geometric curves and surfaces, solid geometry, product structure and configuration management, form feature, shape, tolerances, finite element modeling, drafting, electrical, and presentation (for graphics). The stated objective is to develop, approve, and publish version 1.0 of PDES during 1989.

There are four broad implementation levels, or categories, that encompass different computer architectures and implementation technologies that have been defined for PDES: Level 1 is a passive file exchange (computer to computer); Level 2 is an active file exchange (systems exist to interface applications with the file to allow on-line access), Level 3 is a shared database access approach; and Level 4 is an integrated product knowledge base.

In order for PDES to become a reality, there must be a convergence of several activities:

- a research base of implementing technologies,

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72. Howard Bloom of the National Institute of Standards and Technology contributed to this section.

- development of a specification for product data representation in digital form,

- implementations in software,

- validity checking and testing methodology,

- guidelines for usage in identified applications areas, and

- use in production.

PDES is an extremely large undertaking. The recent formation of an industry-funded cooperative, PDES Inc., to accelerate implementation is a major step toward solving the problems and is attracting wide DoD and industry support.

B.2.2.2.1 PDES Issue

A major issue concerning PDES has been raised by the community of electronic engineers. They view PDES as totally driven by the needs of airframe (mechanical) designers and have expressed dissatisfaction with the direction of the resulting proposed standard specifications. They feel that electronic design, by the nature of the designs themselves and by the nature of the design process, is fundamentally different from structural design and that these differences place radically different requirements on the information representations. Electronic engineers contacted have expressed frustration with failed attempts to get the PDES community to understand these differences and take appropriate action.

DoD, through the CALS initiative, is in a position to provide leadership in getting this issue addressed. In addition to the CALS initiative, DoD is an important customer of many of the companies that are involved in the PDES development. Because of the highly integrated, electro-mechanical nature of many of DoD's systems, DoD has a compelling interest in resolving the issue of getting PDES to be able to capture electronic designs in a way that satisfies the requirements of electronic engineers.

B.2.2.3 Computation

As an example of concurrent engineering presented during the workshops, many companies use computers to support the design process. At some stages, however, particularly the earliest conceptual design stages, computers may not be used, even by teams that are practicing concurrent engineering. Some very simple designs may also be conceived, refined, and transitioned to production using manual techniques. The exceptions notwithstanding, computers are widely used in contemporary design processes and their use is closely associated with concurrent engineering.

Concurrent engineering places additional demands on computing support. Members of the multifunction team analyze the effects of design features and plan the production processes at an earlier stage in the design cycle. To avoid imposing delays on the schedule, team members use computer simulations and other manipulation techniques as previously discussed.

The computation needed for concurrent engineering includes database management, expert systems, graphics, simulation, numerical computation, translation and compilation,

and data communication. These manipulations frequently consume substantial computer resources (memory and cpu cycles). The deployment of certain classes of computer hardware continues to be closely associated with the ability to perform concurrent engineering without imposing unreasonable schedule delays.

Specific examples of this class of technology include: supercomputers, parallel architectures, RISC architectures, and advanced workstations. Improvements in these technologies support concurrent engineering, but appear to be happening independently of it.

B.2.3 Production Technologies

Although the scope of this study concerns the design phase of weapons system development, at least one class of production technology that can be considered using concurrent engineering was found. The ability to remove unnecessary constraints on the decision space and to delay making premature decisions contributes to an enhanced concurrent engineering process. Production technologies that allow greater flexibility in planning the production process and production technologies whose capabilities are known to the designers provide this ability.

A variety of research and development efforts in flexible manufacturing with direct capability to couple the manufacturing cell to the design environment has recently emerged. These efforts need to be coordinated, particularly to ensure their application to concurrent engineering.

The methods of on-line quality control such as SPC were first applied on the production line and produced information that was fed back upstream into the design process, so can the flexibility and information provided by better manufacturing technologies known as flexible manufacturing systems (FMS), be fed back into the product and process design to support concurrent engineering. In some cases new production techniques give the designers new options for materials and functions. The ability to use these options in ways that achieve the goals of concurrent engineering would be impossible without many of these new devices. This relationship of production technology back to the design function is a natural complement to the forward focus of design on production and life-cycle support.

B.3 Formal Methods

This section describes some of the formal methods used in concurrent engineering. Companies reporting significant progress in achieving the goals of concurrent engineering typically use one or more of these methods.

The listing is not exhaustive and use of these methods without the engineering process initiatives will not guarantee successful implementation of concurrent engineering. These methods should be considered tools that can be applied in support of a scientific approach to problem solving. The study team did not establish a ranking by which one method could be considered "better" than another. At this stage the study indicates that companies reporting success in reducing cost, improving quality, and cutting time-to-market often use some of these methods. At the September workshop, the participants developed the following list of methods.

1. Quality Function Deployment

2. Threat Analysis

3. Technology research and transfer

4. System Design, Parameter Design, and Tolerance Design (Taguchi Method)

5. Testing Methods

6. Problem History Feedback

7. Design for Simplicity

8. Design for Assembly

9. Rule-Based Design

10. Simulation (Soft Mock-up)

11. Common Parts Database with Reliability, Maintainability, and Producibility Information

12. Pugh Concept Development

13. Fault Tree Analysis (FTA)

14. Failure Mode Effects Analysis (FMEA)

15. On-line Quality Control

16. Design of Experiments

17. Response Surface Methods

18. Evolutionary Operations (EVOPS)

19. Exploratory Data Analysis

20. Statistical Graphics

21. Group Technology

22. Value Engineering

23. Measurement Methods

24. Operational Definitions

25. Ishikawa's Seven Tools (Graphs, Histograms, Cause-and-Effect Diagrams, Check Sheets, Pareto Diagrams, Control Charts, Scatter Diagrams)

26. Foolproofing

A ranking of the importance of these methods was not developed. Even if such a ranking could be developed for a narrow sector of the defense industry, there is no assurance that a particular engineer or manager could rely on it for guidance when faced with a particular problem. In many domains, familiarity with some minimal set of tools is seen as entry-level qualification and experts are the individuals who understand a wide variety of

methods and can apply the correct approach to the prob\.·• at hand.

Figure B.1 shows the number of times that use of some tool was mentioned during a 1987 Japanese conference on Quality Circles.[73] It confirms that many different methods are used by successful companies.

73. Ikuro Kusaba, "Statistical Methods in Japanese Quality Control," *Societa's Qua'lita'tis, Vol 2, No. 2,* (May June 1988), Union of Japanese Scientists and Engineers.
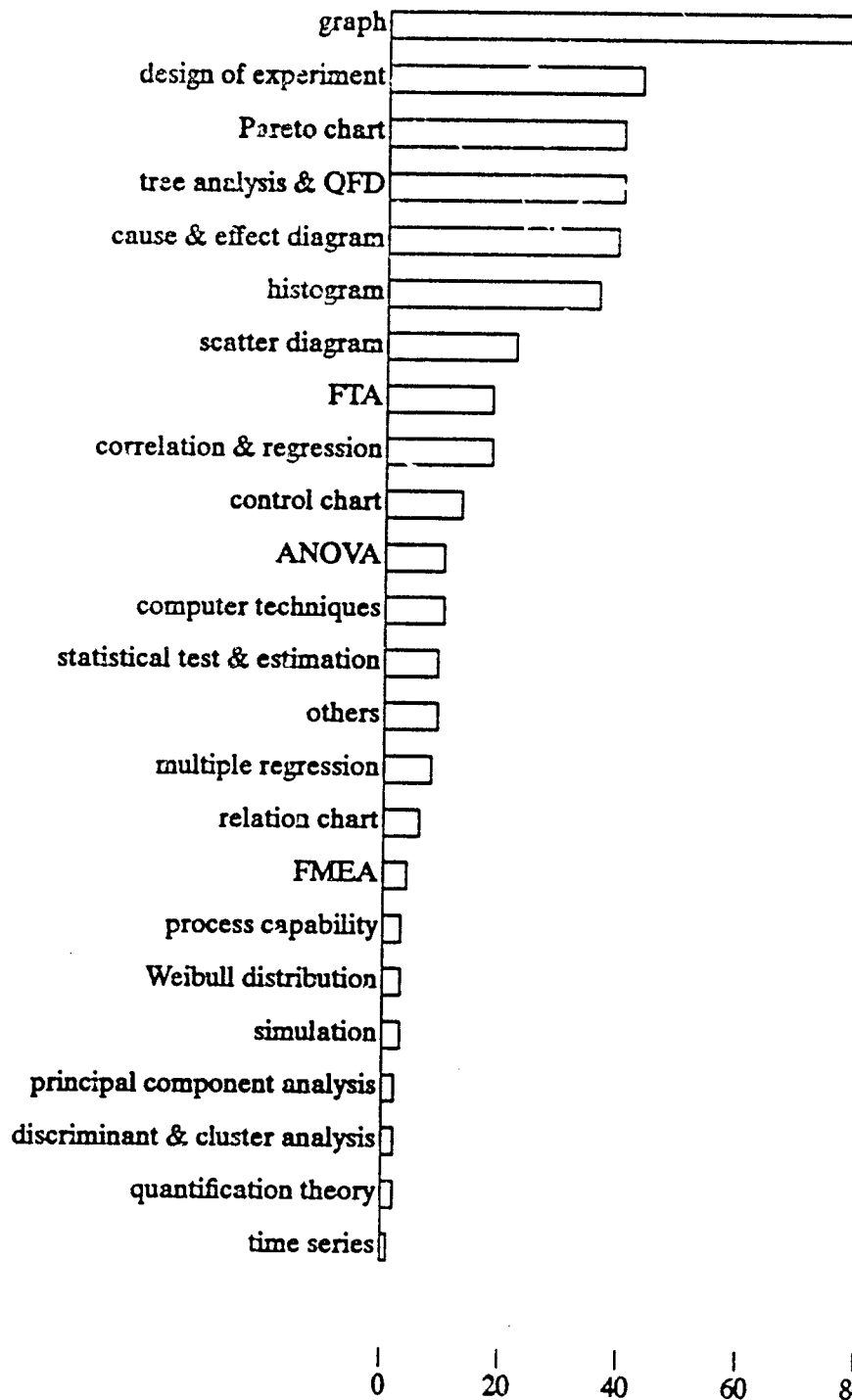
Figure B.1 Reported Use of Methods in the 1987 Annual Quality Circle Conference

Next, the methods that were most frequently mentioned during the workshops are presented. They are described in a sequence that roughly approximates their order of historical introduction.

B.3.1 Process Measurement and Control

This section describes the methods used to evaluate an existing process. Although process control methods are widely used in manufacturing areas, there is no intrinsic reason to restrict their application to manufacturing. Many noteworthy improvements have resulted from applying process control to service sectors and to design problems. To make it clear that the discussion is not restricted to manufacturing, the notion of a generic process and the role of variability in a process and its products are introduced. The discussion includes a sketch of the progress in this area. The section concludes with a summary of the principal process measurement and control techniques and the issues associated with their use.

A process is an intuitive concept representing some collection of people, equipment, and operating procedures that is intended to provide some product or service for an organization. A process accepts inputs from suppliers and transforms them into a product for a customer. We allow a broad interpretation of the terms supplier and customer and they can include both internal and external (to an organization) relationships. Similarly, the input and product can be raw material and finished product or value enhanced transformation of the raw material. In a service organization, both the raw material and the product can be some form of information.

Figure B.2[74] shows a process as a "black box". It shows the relationship among a process, its supplier, and its customer. It is intended to imply that the internal details of the process are not important to the evaluation of the process.[75] In fact, it is customary to suppose that the internal controls remain fixed during an evaluation. Controls are adjusted only after an evaluation produces some information about the output of the process.

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74. Roger Ackerman, Roberta Coleman, Elias Leger, and John MacDerman, *Process Quality Management and Improvement Guidelines*, Publication Center, AT&T Bell Laboratories (1987), p. 8.

75. We assume that mechanisms exist to adjust the operation of the process and these mechanisms are called controls.
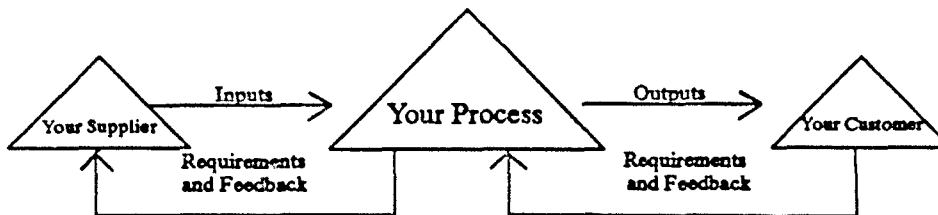
Figure B.2. Process Model

An evaluation consists of measuring one or more attributes of the product and comparing those measurements with their ideal values. The ideal values are the target values that have been found to satisfy the customer's requirements. A product's quality is a measure of the difference between its actual attributes and its ideal or target values.

It is axiomatic that an observer who is willing to perform sufficiently precise measurements will always find variability among products produced by a process. Wheeler[12] notes that in manufacturing, the earliest approach to dealing with variability was the introduction of specifications. Specifications were upper and lower control limits for acceptable variability of a product. Products either satisfied the specifications, or they did not. Those meeting the specification were shipped to the customer while the failures were either reworked or scrapped. Inspection was introduced to determine which products met the specifications. Disagreements between suppliers and customers frequently arose as manufacturers sought to relax the specifications to reduce costs of scrap and rework, whereas

customers wanted tighter specifications to improve product performance through reducing variability. He points out that this conflict obscured the important issue of how to manufacture parts with as little variation as possible. The work of Walter Shewhart as extended by W. Edwards Deming provides a new perspective on the importance of reducing the causes of variation. Based on experimental data, Shewhart concluded

"while every process displays variation,
some processes display controlled variation,
while others display uncontrolled variation."[76]

Controlled variation is equivalent to a process whose internal controls and input are fixed. If nothing changes, the output of the process will exhibit variation, but the statistical distribution of the product characteristics will be constant. Controlled variation permits one to make statements about the probability that the product characteristics will fall within some range of values. Uncontrolled variation does not permit such prediction. Shewhart postulated that special factors,[77] usually associated with some inconsistency in the process, are the cause of uncontrolled variation.

In order to reduce variability in the product, management must first identify and remove the special causes of inconsistency in the process and then institute a policy of continually improving the process so as to reduce its controlled variation.

Management has found that using the Shewhart concept of variation is a powerful method for controlling and improving processes. In the United States, American National Standard, ANSI Z1.1-1985, *Guide for Quality Control Charts*, Z1.2-1985, *Chart Method of Analyzing Data*, and Z1.3-1985, *Control Chart Method of Controlling Quality During Production*, are available for the American Society for Quality Control. In Japan, manufacturers have used these methods since the 1950s. There is extensive literature concerning these methods (see Deming [13], Juran [14], and Ishikawa[15]).

Managers in the United States and Japan have used techniques of statistics to measure performance and they have implemented management techniques that are consistent with the Shewhart concept. The results have been reduced product variability, improved product quality, and reduced cost of nonproductive activities such as inspection and rework.

The first step in improving performance is to evaluate the current process. The techniques of evaluating a process to learn if the variability is controlled or uncontrolled are called statistical process control.

Statistical process control is based on the hypothesis that if a process is stable, then one can measure a product characteristic that reflects the behavior of the process and the

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76. Donald J. Wheeler and David Chambers, *Understanding Statistical Process Control*, Statistical Process Controls, Inc., Knoxville, TN 1986, p. 5.

77. Special factors are causes of variability associated with some change of process controls that alters the process. Special factors are often called special causes. Some examples of special causes are changes in the quality of supplies, wear and aging of tools, new personnel, or new procedures.

measured characteristic will have a common distribution (in a probabilistic sense). That is, different sample groups of the product from the process will have the identical statistical distribution of the characteristic.

Statistical process control selects sample groups and conducts simple statistical tests to verify the hypothesis. As long as the tests do not show that samples have different distributions, one assumes that the process is stable and concentrates on incremental improvements for the process. If a test indicates that the distributions are not identical, then one looks for the special causes of variability. When such causes are found, they are eliminated. This algorithm is repeated until the process becomes stable. When a process is stable, further improvement can only be achieved by changing the process.

The most common type of test is based on a series of sample groups. For each group, a group average and group range are recorded. After a sufficient number of sample groups have been drawn, the average of the group averages and the average of the group ranges are computed. If the original hypothesis of common distribution is correct, then the group averages will be *approximately* normally distributed with an average that is approximately the same as the average of averages, and a standard deviation that has a known relationship to the average range. From the properties of the normal distribution, it is known that the variation of the sample averages and ranges will tend to cluster about the grand averages and only in very rare occasions diverge by more than three times the standard deviation. For this reason, the most common indicator of a special cause is a sample average that is more than 3σ (where σ is the symbol for the standard deviation) away from the grand average.[78]

A stable process that yields products which satisfy the customer's needs may, at some time, become unstable. Instability may arise from special causes as previously noted. Continued monitoring of the process through statistical process control can detect the transition to an unstable state; hence management may infer the presence of special causes. A process that continues to pass the tests isn't always a stable process, but the probability is very small that a unstable or chaotic process will continue to produce output that passes the tests.

Several different charts are used in statistical process control for conducting these tests. When the value of the characteristic can be measured, the $\bar{x}$ and R charts are used; when the fraction of defective products is the characteristic being measured, the p chart is used; when the overall number of defects is being measured, the c chart is used; and when the overall number of defects per unit is measured, the u chart is used.

Although the Shewhart approach to variation focuses on the process instead of conformance to specification, practitioners of process control do not ignore specifications. Engineers and designers continue to define specifications and statistical tolerances as part of the design effort. A production process is said to have a *process capability index*, c_{pk}, defined as follows:

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78. Other tests are also available including measuring runs of samples on one side of the average, but they share a common thread—namely that if the hypothesis is true, then a test failure is a very rare event.

Let

$$c_{pk} = \frac{Z}{3\sigma}$$

where

$$Z = \min\{(\overline{\overline{X}} - lower\ specification\ limit),(upper\ tolerance\ limit\ -\overline{\overline{X}})\}$$

and $\overline{\overline{X}}$ is the grand average.

The process capability index is a measure of the ability of a process to produce quality products.

In addition to statistical process control charts, Pareto diagrams, cause and effect diagrams, and PERT charts are used to evaluate how processes can be improved.

Although process measurement methods were first introduced for manufacturing processes, their use in not restricted to manufacturing. SPC has been used to evaluate and eventually improve engineering processes. It is also a means to gather accurate information that can be fed back into the product and production design processes. It can be used to support achievement of the fourfold goals of concurrent engineering.

The CUSUM[79] chart provides an alternative method of recording observations and it has the advantage of helping identify changes in the process mean output. Observations, y_i can be plotted by their cumulative sum, $\sum_{i=1}^{i} y_i$, against time t. Alternatively, one can use the cumulative sum of the deviations from the target value

$$d_i = y_i - C$$

where C is a constant (presumably the target value) The CUSUM chart plots $\sum_{i=1}^{T} d_i$ against time. It allows one to easily see when a process mean begins to vary from the target.

The CUSUM control chart was first introduced in England by Page.[80] Other important early contributors are Barnard,[81] Ewan and Kemp[82] and Johnson and Leone.[83] Ewan[84]

79. J. Stuart Hunter, "The Exponentially Weighted Moving Average," *Quality Technology*, Vol. 18, No. 4 (October 1986), p. 204.

80. Page, E.S., "Continuous Inspection Schemes," *Biometrika*, 41 (1954), pp. 100-115.

31. Barnard, G.A. "Control Charts and Stochastic Processes," *Journal of the Royal Statistical Society*, Series B 21 (1959), pp. 239-271.

82. Ewan, W. D. and Kemp, K. W., "Sampling Inspection of Continuous Processes with no Autocorrelation Between Successive Results," *Biometrika* 47 (1960), pp. 363-380.

83. Johnson, N. L. and Leone, F.C., "Cumulative Sum Control Charts, Parts I, II, & III," *Industrial Quality Control*, 18 (1962), pp. 29-36.

84. Ewan, W. D., "When and How to Use CUSUM Charts," *Technometrics*, 5 (1963), pp. 1-22.

provides an excellent expository article on the CUSUM, and a small text elucidating CUSUM procedures was authored by Woodward and Goldsmith.[85]

The process control methods discussed previously have proven beneficial in numerous applications, but they have one disadvantage: they report historical data. Hunter[86] describes a technique for maintaining control charts that can be used as a predictive tool. The technique, exponentially weighted moving average (EWMA), is a statistic that gives less and less weight to older data. A plotted point on an EWMA chart can be given a memory that controls the rate at which its importance is diminished. The EWMA plot equals the present predicted value, y_t plus some constant λ times the present observed error of prediction. Thus,

$$EWMA = \hat{y}_{t+1} = \hat{y}_t + \lambda e_t.$$

Control limits on the predicted values are used to show when the predictions become unreliable. When predictions fall outside the control limits, preventive action can be taken with process controls.

As more information becomes available in real time in the factory, researchers and practicioners are beginning to measure not only the product parameters but also the changes in process control parameters. Such applications are similar to control engineering.

B.3.2 On-Line Process Control

Walter Shewhart developed the statistical quality control charts in the 1930s. In the late 1950s, Page and Barnard introduced *Cumulative Sum Charts* which respond more quickly to change in mean level. (DuPont boasts of currently using more than 15,000 of these charts.) In the 1960s and 1970s, Box and Jenkins and later MacGregor and Hunter helped to relate statistical time series analysis and automatic feedback-feedforward control. In the 1970s, Box and Jenkins showed how to take account of the cost of adjusting the process and the cost of being off-target in the design of an optimal scheme. In 1973, Kartha discussed how a control system could be optimized with respect to the cost of frequency surveillance.[87] Taguchi[88] outlines four steps to achieving on-line process control. He provides recommended formulae for determining the optimum correction interval, the prediction of the characteristic value, and the amount of correction. Hayes[16] describes four levels of process control: reactive, preventive, progressive, and dynamic. Progressive control is applies to changes in existing processes, including product design, and it requires partnership with product and process engineers. Dynamic control applies to the science of process and it involves

85. Woodward, R. H. and Foldsmith, P. L., *Cumulative Sum Techniques*, Oliver & Boyd, London (1964).

86. J. Stuart Hunter, "The Exponentially Weighted Moving Average," *Journal of Quality Technology*, Vol. 18, No. 4 (October 1986), pp. 206-210.

87. George Box, Center for Quality and Productivity Improvement, University of Wisconsin, August 1983.

88. Genichi Taguchi, *Introduction to Quality Engineering*, KRAUS International Publications, White Plains, NY (1986), p. 38.

scientists and advanced engineering departments.

B.3.3 Design of Experiment

Experimental design was invented and developed in England by Sir Ronald Fisher and his colleagues and students in the 1920s. In particular, Fisher pointed out how enormous gains in the efficiency of experimentation could be achieved by changing factors, not one at a time, but together in a factorial design. He introduced the concept of randomization, so that, for example, trends due to unknown disturbing factors, would not bias results, the idea that a valid estimate of experimental error could be obtained from the design, and blocking to eliminate systematic differences introduced by using different lots of experimental material, for example. He also invented and developed methods for analyzing such experiments via the Analysis of Variance and Student's t-test. Fisher's ideas although originating in agriculture were quickly adopted in medicine and biology throughout the world and for the last 50 years have been the standard means of experimenting there.

In the 1930s Fisher's ideas were also introduced into industry. At that time, The Industrial and Agricultural Section of the Royal Statistical Society was inaugurated in London and papers from industry on applications to manufacture of glass, light bulbs, textiles, etc., were presented and discussed. This led to new statistical methods: fractional designs were first used by Tippett in 1933 to improve a spinning machine and variance component analysis was developed by Daniels in 1935 to reduce variation in textiles.

During World War II the need for designs which could screen large numbers of factors led to the introduction of fractional factorial designs and other orthogonal arrays respectively by D. J. Finney (a student of Fisher) and by Plackett and Burman, two statisticians working in Britain's Ministry of Defense. In 1947, orthogonal arrays were named and further developed by C. R. Rao. Further notable work on these designs were performed in this country by Kempthorne, Sieden, Addelman, Box, Hunter, and others.

These designs have been widely applied in industry and many successful industrial examples are described in papers and books dating from the 1950s and, in particular, by a highly respected engineer and statistician, Cuthbert Daniel. Daniel also invented a very simple but important and effective way of analyzing the designs using normal probability plots.

In the early 1950s, Box, who was then working for the Imperial Chemical Industries developed new techniques called response surface methods for the improvement and optimization of industrial processes experimentally. Initially when systems may be far from optimum conditions, fractional factorial designs and other orthogonal arrays were used to estimate a path of steepest ascent to increased response. Once the maximum was approached, second degree approximations were used with new types of designs, introduced by Box and Hunter and others, to estimate the necessary coefficients. Further analysis was used to study ridge systems which might allow simultaneous maximization of more than one response (e.g., maximum yield with minimum impurity). Response surface methods are routinely used by such companies as 3M, DuPont, General Electric, Allied Signal, and Dow Chemical to improve and optimize their processes, and many successful industrial applications have been described in numerous papers and books published over the last 30 years.[89]

B.3.4 Robust Product Design

This section briefly describes the robust product design[90] methods developed by Genichi Taguchi. Robust product design starts with a concept that quality can be viewed as a loss to society associated with a product. This loss can be minimized if some characteristic of the product has an ideal target value and the loss increases as the square of the distance as the characteristic varies from the target value. Using this concept, it no longer suffices to produce items that are "within specification". Taguchi recommends use of statistically designed experiments to help designers find the parameter settings that will result in a product whose important characteristic is consistently close to the ideal target despite the presence of manufacturing variations or the effects of age. Moreover, he recommends that these values be selected using the least expensive materials.

The design steps involved are system design, parameter design, and tolerance design. System design is used to find the best technology for a product. Parameter design finds the parameter values which optimize the product loss. It reduces the effects of variability. Tolerance design selects the tolerances that must be used in manufacturing to assure minimum loss after the product is manufactured and is being used by the customer. It reduces the causes of variability in a product.

The term parameter refers to any aspect of the product or process design that is subject to control by the respective designer. A parameter might be the composition of the materials used in a process, the shape and number of parts in an assembly, the temperature setting for a particular thermostat or some other factor that can be controlled. Parameter design consists of selecting the set of parameter values for both a product and the process used to make it so that some particular measure of success will be improved. The improvement will not always be an optimization in the mathematical sense.[91]

Parameter design, including the use of statistical experiments, has been part of the design process (parameter values are determined by engineers) but it has traditionally been practiced when the goal was some improvement in a performance measure. It has only recently been used in the United States to reduce variability. It is now used to provide increased quality and lower cost. Although parameter design to reduce variability may be accomplished by a variety of *ad hoc* methods,[92] Genichi Taguchi[17] uses the term Quality

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89. We are indebted to Dr. George Box, Center for Quality and Productivity Improvement, University of Wisconsin-Madison, for contributing the information in this section.

90. The terms "robust design" and "robust engineering" are used interchangeably with "robust product design".

91. There are at least three reasons why mathematical optimization may be impractical: 1) the function describing the effect of variation of the parameters is usually unknown; 2) best engineering judgment might be inadequate for identifying the correct range of parameter values containing the value that achieves the optimum result; and 3) the optimum result may lie in a region where the function is not stable (that is small changes in a parameter could cause large variation in the output).

92. Jeffrey A. Morrow, "An Investigation of the Penetration of Taguchi Quality Engineering in Five U.S. Corporations," June 1988, p. 58. The author notes Xerox technical staff developed techniques for engineering design optimization called "Stress Testing/Operating Windows" or "Design for Latitude" and these were philosophically similar to Taguchi's approach.

Engineering to describe an approach to achieving both low cost and improved quality. Other organizations have adopted the term "robust design" and this report follows that convention.

The benefits of robust design have been demonstrated in automobile manufacturing, electronic component production, computer operating systems, engine design, optimization of IC chip bonding process, ultrasonic weld process optimization, and design of disc brake systems. The study term heard reports of many applications of this technique and in almost every case the results have been impressive.

Robust design involves the following principal steps:[93]

1. Plan an experiment.

   a. Identify the main function.

   b. Identify side effects, and failure modes.

   c. Identify noise factors and testing conditions for evaluating quality loss.

   d. Identify the quality characteristic to be observed and the objective function to be optimized.

   e. Identify the controllable parameters and their most likely settings. (This step relies heavily on engineering judgment.)

   f. Design an experiment and plan an analysis procedure.

2. Perform the experiment.

   a. Conduct a statistically controlled experiment and collect the data.

3. Analyze and verify the results.

   a. Analyze the data.

   b. Determine the important parameters and their best settings, and predict the performance under these settings.

   c. Conduct a verification experiment to confirm the results at the optimum settings.

B.3.4.1 Comments on Robust Design

The issues concerning robust design are:

1. Do these methods offer promise during the design process?

2. If the techniques can be used during design, are they useful in the design of systems as complex as weapon systems?

3. Is the loss function a meaningful concept when evaluating weapon systems?

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93. Madhav S. Phadke, *Quality Engineering Using Robust Design*, to be published by Prentice Hall, Inc.

4. Are the techniques used to conduct and analyze experiments independent of the goals of variability reduction (that is, is the designer free to chose different metrics for the objective function)?

5. What are the known limits of parameter optimization using Taguchi or other techniques?

6. What new techniques can be developed to improve on these techniques?

7. Should one consider alternative approaches to experimentation rather than a single experiment?

During the course of the study the team became aware of differences of opinion regarding the best approach to parameter optimization. One school favors use of Taguchi methods, another group favors use of other statistical tools. The controversy is not limited to the United States.[94] IDA cannot, at this time, make a determination regarding the superiority of either approach. There are objections to the statistical techniques recommended by Taguchi. The various examples from industry demonstrate that when experiments are properly designed and when they yield measures on both the mean and the variance, the insights which accrue can be used to improve designs. Good results have been reported by companies using Taguchi methods as well as classical methods.

In some industries, particularly the chemical industry, there is a tradition extending over several decades concerning the use of statistical methods including design of experiment. In other industries, statistical methods have only recently been rediscovered. It is possible that there is a correlation between use of different design-of-experiment methods and the type of industry using a particular method.

It clear that DoD should not impose either approach on its suppliers. Contractors who must decide which method is best for their particular situation can be evaluated on the results of their own choice.

B.3.5 Evolutionary Operation

Process control methods seek to improve process consistency by finding and removing special causes of variability. Robust design improves process resistance to noise by finding parameter settings for product and process design that are less sensitive to noise. Evolutionary operation (EVOP) uses a process as a continual source of experimental data. The process is disturbed in a controlled fashion during normal operations and the results are carefully recorded and analyzed. [Box[18]] The analysis shows how the process can be adjusted for evolutionary improvement.

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94. Myron Tribus reports that Japanese companies he visited on a tour of Deming Prize winning companies did not use Taguchi methods although they were aware of them. He quotes Ikuro Kusaba, "the basic useage of the orthogonal array has been widely adopted since the 1950s as a type of the design-of-experiment method. By contrast, its complicated usages represented by the pseudo-factor method, and the concepts of SN-ratio and on-line QC are the choice of only a small number of people." Myron Tribus, unpublished correspondence, 1988.

Evolutionary operations raise an interesting challenge for DoD contractors. If the customer has entered a contractual agreement that includes a detailed description of the production process, is the company free to vary that process slightly in order to conduct EVOP, and thereby potentially improve the quality of the outgoing product?

B.3.6 Questions

This study raised several issues that are associated with concurrent engineering during the discussion of methods. These issues are the result of both discussions during the various workshops and the authors' judgment. Two concerns about concurrent engineering were shared by many of the workshop participants: 1) Will "concurrent engineering" become another specialty that generates a new reporting system, new terms, new class of "experts"? and 2) Are particular Japanese methods being forced on U.S. manufacturers?

Some workshop participants questioned the level of detail with which some method might be specified by DoD. DoD 2000 was cited as an example of both overspecification and technological progress. SPC was also mentioned as an area where overspecification by DoD was a concern. Several participants said that although many companies recognize the benefits of using SPC, their unique circumstances might lead them to select some particular method of collecting and analyzing the data. They did not want DoD to impose a particular technique that might not be appropriate for their situation.

In the judgment of the study team, the concerns raised by these questions are legitimate. If concurrent engineering initiatives merely generate another specialty with its associated layer of new reports, then the DoD will have missed an opportunity to achieve significant improvements. Furthermore, there is evidence that DoD and military specifications are often obsolete. This implies a slow process for creating and maintaining such information. If that is the situation, then overspecification will impose suboptimal methods on future defense contracts, even if the methods specified are optimal today.

The resistance to adopting Japanese methods was clearly evident in many discussions. There were several reasons given for the resistance. The following arguments are representative of the objections raised to adopting Japanese methods:

1. Japanese methods are dependent on unique aspects of the Japanese culture (homogeneous society, greater loyalty, less individual competition, etc.) and will not work with U.S. workers;

2. there are better methods available that were developed in U.S. (the Japanese methods being merely adaptations of U.S. techniques from the start); and

3. resistance to copying external behavior of another organization. The third reason can be argued as follows: "Successful methods are merely a manifestation of internal vitality in a company; they did not create that vitality." Of course, many organizations resist adopting any new concepts that were not originated locally, that is the so called "not-invented-here syndrome".

   Not all U.S. companies share the same resistance to adopting these methods. Some companies have achieved notable success that they attribute to use of the same methods.

Our observation of different companies leads us to conclude that although DoD may wish to avoid imposing any of the Japanese methods, companies electing to undertake a significant cultural renewal in order to gain competitive advantage should carefully consider using SPC, quality engineering principles, and a well-defined systems engineering process such as QFD. There is no compelling evidence that such methods are the ultimate solution to system design, but they have yielded impressive results when applied as part of a broader company effort to attain excellence.

Although the question of whether to adopt particular Japanese methods is arguable, there is consensus that "concurrent engineering" should not become another specialty. The problems that concurrent engineering initiatives are trying to solve are, in large measure, the result of a proliferation of functional specialties within government and industry. These specialists tend to form communities that are called "stove pipes". Communication tends to be confined to the different communities and they extend from the DoD through the contractor and subcontractor. Horizontal communication is less effective when the influence of "stove pipes" is strong. Because horizontal communication is essential for concurrent engineering, any initiative that tends to create a new "concurrent engineering" specialty will be a fundamental contradiction of its goals.

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C. A CONCEPTUAL FRAMEWORK FOR CONCURRENT ENGINEERING

Concurrent engineering as defined in this report is an idea just now evolving in terms of its theory and practice. As concurrent engineering methods and technologies allow people to perform new forms of analysis and synthesis, engineering functions are being redefined and design theories and methods are being revised. In order to aid in the understanding of and programmatic planning for the evolution of concurrent engineering, a conceptual framework has been created. This framework provides a structure so that researchers, developers, sponsors, and practitioners can discuss the issues, barriers, and opportunities of concurrent engineering. It provides a relational structure for answering many of the "how" and "why" questions of concurrent engineering.

The conceptual framework could be detailed for the evolution of cultural, organizational, management, or technical issues. The detailed version presented here is aimed at technical issues. The reader must realize, however, that the success of methods and technology depends on the effectiveness of the related management and cultural changes.

Also, it is very important that the reader understand that many useful concurrent engineering methods and technologies exist now. *There is every reason to proceed now to effect concurrent engineering in the DoD and its industrial base. There is no reason to await the evolution of further methods and technologies.*

Given that this section details the framework in terms of methods and technology, it could deal either with current methods and technology, evolving methods and technology, or both. Since the section is aimed at people planning technical research and development efforts, the framework has been detailed only in the area of evolving methods and technology.

The framework structure, shown in Figure C.1, relates resources to objectives, and vice versa. The design objectives (Component 1) are related to the critical functions (Component 2) of concurrent engineering necessary to achieving those objectives. To achieve these functions, they, in turn, require specific capabilities (Component 3). Finally, these capabilities are constructed from technical building blocks (Component 4). This framework incorporates such causal relationships. That is, if one moves from left to right across the framework, the question "how" is answered. If one moves from right to left, the question "why" is answered. For example, how do we achieve the design objectives? The answer is: by providing the critical functionality.

Figure C.2 applies this framework structure to the field of concurrent engineering. The design objectives are simply to acquire the product which has the highest quality, at the lowest cost, within the shortest time. The cost here includes both design and production cost as well as all other costs during the product life cycle. Quality, as defined earlier in the report, incorporates elements of both product performance and reliability. The time relates to both the *time to availability* for a new weapons system and the *time for delivery* in response to demand for current systems. While these are the objectives of any design process, the concurrent engineering process offers unique opportunities to achieve designs that are:

- responsive to the field operator's needs,

- provide explicit and objective trade-offs between conflicting objectives, and
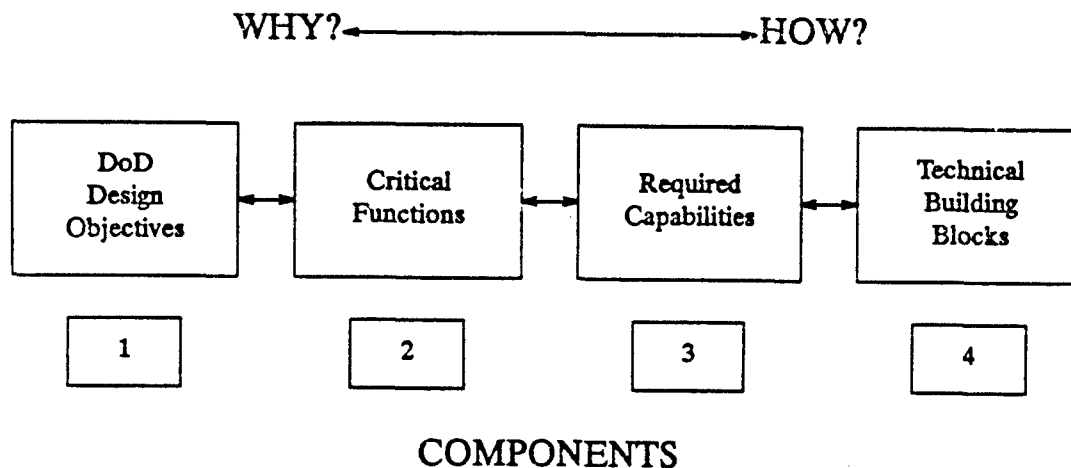
WHY?◄───────────────────────►HOW?

DoD Design Objectives	Critical Functions	Required Capabilities	Technical Building Blocks

| 1 | 2 | 3 | 4 |

COMPONENTS

Figure C.1. Framework Structure

• provide for continuous improvement.

These opportunities are provided by three critical functional improvements in the concurrent engineering design process. These critical functions are presented in Component 2 (Figure C.2) and relate explicitly to the timing, process, and philosophy of design accomplished through concurrent engineering. Within concurrent engineering, the timing provides an early and continuous dialogue between customer and vendor functions. The process provides a simultaneous participation of all functions and the concurrent product and process optimization. The philosophy is one of continuous improvement against current and projected product and process baselines.

In order to effect these functions of concurrent engineering, organizations and their customers must achieve certain capabilities within all functional areas from design through manufacture to use, service/maintenance and disposition). Nine of the capabilities are listed in Component 3.

Finally, these special capabilities are based on technical building blocks. These include data structures and data processing, concepts and systems, frameworks and architectures, tools and models, manufacturing systems, and design processes. The technical building blocks are presented in Component 4. They exist at varying levels of maturity, ranging from concepts in research laboratories to working hardware and software systems and manufacturing companies. This framework provides a system within which leaders from government, industry, and academia can focus their efforts on investments in order to provide additional knowledge required in the various technical areas, and hardware and software systems built upon this knowledge. By moving from right to left across the entire framework they can also justify investments in research, development and hardware and software in terms of their provision of new capabilities and functions necessary for the effective pursuit of

COMPONENT 1 DoD OBJECTIVES	COMPONENT 2 CRITICAL FUNCTIONS	COMPONENT 3 REQUIRED CAPABILITIES	COMPONENT 4 TECHNICAL BUILDING BLOCKS
Reduced Cost	Early, complete, & continuing understanding of customer requirements and priorities.	Capture data on comparable products, processes, & support (lessons learned).	Data Processing & Data Structures
		Define and capture data for new weapon system product, process, & support. (complete and unambiguous description)	
		Synthesize requirements into design of product, process, & support.	Frameworks/ Architectures
		Validate design of product, process, & support.	
Reduced Time	Translation of requirements concurrently and in an integrated fashion into optimal products and manufacturing and support processes.	Manage product, process, & support data.	
		Disseminate product, process, & support data.	Tools & Models
		Deliver product or data for manufacturing & supporting product.	
Increased Quality		Rapid Prototyping	
		Process Robustness	Manufacturing Systems
	Continuous review and improvement of product, process, & support characteristics.	Intelligent oversight for impact assessment of changes.	
		Proactive, concurrent availability of current design.	Design Processes

Figure C.2 - Concurrent Engineering Framework

DoD objectives.

C.1 Component 1 — DoD Design Objectives

The overall objectives of the DoD acquisition process are the subject of considerable discussion in other parts of this report. A short summary of the key objectives follows:

- High quality as reflected in

  — High product performance levels

  — High utility and reliability in a variety of operational environments

- Low cost

  — Of product manufacturing (purchase price)

  — Of product use

  — Of product maintenance/service

  — Of product disposal

- Short time

  — For development of new product designs and manufacturing processes

  — For delivery of current products

It follows from the definition earlier in the report that concurrent engineering is a system for the achievement of (or, at least, the engineering approximation of) the best possible combination of these objectives. It provides the opportunity for leaders to assess trade-offs and decide among them based on timely, accurate, and objective analyses. To do so, concurrent engineering requires functions related to processes, timing, and philosophy of design.

C.2 Component 2 — Critical Functions for Concurrent Engineering

To achieve the Component 1 objectives, it is necessary to function in new ways with regard to the timing, process, and philosophy of engineering. With regard to the *timing*, there must be an early understanding of the needs of all customers and the requirements of all phases of the life cycle. The *process* must change to ensure an effective and timely contribution of all responsible participants in the design/manufacture/use cycle, and the objective identification and evaluation of trade-offs. The *philosophy* of the entire enterprise must be one of continuous and aggressive improvement. This, in turn, leads to a change in corporate focus from one of reaction to problems, to one of problem prevention.

These three functional changes, timing, process, and philosophy, are critical elements which characterize concurrent engineering. They are the differences between concurrent engineering and "good engineering practice", as it is executed in the U.S. today. All three elements are essential, and of equal priority.

C.2.1 Timing — Early, Complete, and Continuing Understanding of the Customer Requirements and Priorities

To provide effective designs, the team must first understand the customer's real requirements and priorities. When resolving and placing priorities on requirements, the customer and developer must define and evaluate trade-offs. For example, what are the operational environments and performance levels which are an absolute necessity for this system? With regard to priorities, given the choice, would the customer prefer 100 aircraft that perform at Mach 3, or 150 that perform at Mach 2.7? Or, is the availability of a weapons system in one year more important than improving its performance 10% and providing it in 18 months?

There are an interminable number of such questions relating to the trade offs between product performance/reliability, cost, and timing/schedule. In the ideal scenario, there would be an open and active dialogue between customer and vendor. This dialogue would, over time, transform a fairly vague set of requirements into the best specific set of time/cost/performance values available at the time.

To achieve the necessary understanding between the customer and the vendor, the customer must include both those who are "buyers" and those who are "users", including those responsible for the installation, operation, and maintenance of the systems. The vendor must include those responsible for the design, manufacture, and service/repair of the systems. Through the involvement of all these, the team can identify the various required and desired characteristics that will form the basis of the trade-offs of the design process.

In the ideal environment, the needs of the customer (for example, performance levels of the product) would be translated into increasingly more specific characteristics and features of the product. These, in turn, would be related directly to the process operations and capabilities which affect those specific product features. In this way, the "voice of the customer" would remain consistent and be heard by all those defining the product and process, and at all stages of the design process. To accomplish this, there must be both feed-forward and feed-back of information among various functional organizations (for example, the product-design laboratory, the manufacturing-engineering group, and the production-planning section, etc.) and feed-forward between the various time phases of the design process.

Similarly, there must exist a process whereby the customer and vendor can verify that the product, process, and support processes meet the requirements. Like the transmission and translation of these requirements just described, this must first occur at a "macro" level, with some subjective evaluations or objective evaluations which incorporate a significant degree of estimation and uncertainty. As the product and processes become further defined, then the level of certainty and exactness of this verification will increase.

C.2.2 Process — Translation of Requirements

Requirements must be translated concurrently and in an integrated fashion into optimal product definitions, manufacturing processes, and support processes. Here the key elements of improved functionality relate to the concurrency and integration of the creation of product and process definition, and the concurrent consideration of all phases of the product life

cycle. The design process must allow, encourage and, in fact, ensure that

- all requirements of the life cycle are considered and evaluated,

- the cross-impact of various functional decisions are understood and evaluated (with appropriate trade-off analysis),

- critical risks of various design options are identified and addressed early in the process, and

- those responsible for the various functional areas within the development and manufacturing enterprise participate with appropriate levels of responsibility and authority.

To achieve these objectives, concurrent engineering suggests four specific functions.

First, there must be an integrated and continuing participation of multifunction teams in the design of product, process, and support. As the product designers define geometries and tolerances, others must simultaneously define the manufacturing process to achieve them (and the costs and adequacies of these processes). Still others must evaluate the subsystem accessibility and ease of service. In a fully operational system for concurrent product and process design, the information system should have automatic access to the current capabilities and capacities of the corporate manufacturing facilities. This would allow an intelligent system to project the impact of specific product tolerances and volumes on the manufacturing system, and the adequacy of that system to provide the requisite accuracies and volumes. Based on this knowledge, the designers of product and process can project costs at various levels of product/process performance, allowing informed decisions regarding the trade-offs of cost, quality, performance, and timing.

Second, this process of integrating multiple engineering, manufacturing, and management functions must provide for efficient iteration and closure of product and process designs. Each iteration should again involve each of the relevant functional areas for review of the impact of the changes made. This may be done manually through a "marked up blue-line" process, digitally through a process of automatic "flag raising" which notifies affected functions, or even with automated analysis which projects the impact of design changes on the adequacy and/or projected performance and cost of the various life-cycle elements (product capability, manufacturing process, service, reliability, etc.).

Third, the system must identify conflicting requirements and support their resolution through an objective choice of options based upon a quantitative or qualitative comparison of trade-offs, as appropriate. The analysis and modeling described above often lead to the identification of conflicting impact of design alternatives. Obviously, any one change can increase product performance, but also increase manufacturing cost and time to production, and simultaneously decrease reliability. It is critical that any concurrent engineering process explicitly identify, record, and analyze such conflicts and the resultant trade-offs.

Finally, the concurrent engineering process must incorporate an optimization of the product and process design. [Note: The optimization here should not be interpreted as any theoretical optimum of any individual design objective, such as system performance (for example, aircraft speed), but a very best possible combination of the most desirable

objectives as defined by the customer.] This optimization can be based on either (or both) empirical or analytical (theoretical) knowledge. Empirical knowledge can be derived from experts in the field who call upon their experience to project the impact of design alternatives. Also, empirical knowledge can be systematically derived from data collected and statistically analyzed from current products and processes which are in some ways similar or identical to those being considered for a current or proposed system. Alternatively, theoretical knowledge and scientific/engineering analysis can be applied to the evaluation of alternatives. While many examples of such models exist, such as finite element structural models or manufacturing process models, the concurrent engineering objectives will be met only when their application is assured and achieved with speed and ease.

C.2.3 Philosophy — Continuous Review and Improvement of Product, Process, and Support

The improved timing and process of design do not alone achieve the promise of concurrent engineering. The philosophy of the design process must be changed from a one-time effort to achieve an acceptable level of the cost, quality, and time trade-offs, to one of sustained, continuous improvement. Most designs are created through a sequence of phases which occur over a targeted period of time, and involve a series of transfers from "concept people" to "detailers". Thus, when the sequence is finished, the design effort is finished, and the value of the design is determined. Changes after that time are considered undesirable engineering changes. While change as a reaction to unforeseen problems and trade-offs is indeed undesirable, and usually costly, the philosophy of sustained, continuous improvement can lead to many changes in the early design stages. These changes each lead to some net improvement in the overall collection of trade-offs.

There are four specific functionalities which contribute to this continuous improvement.

First, it is necessary to have open and continuous communication. This communication exists both between customer and vendor as well as within the customer's and vendor's organizations.

Second, a complete (necessary and sufficient) and unambiguous statement of the users' requirements must develop, including the priorities of various requirements to be applied in the case of trade-off analysis. This can be attempted in the initial statement of requirements, but that is extremely difficult to finalize so early in the design process. These requirements and specifications would better evolve as greater knowledge and certainty emerge through the concurrent engineering process. In fact, the very nature and objectives of concurrent engineering encourage the continual evolution of requirements and priorities based on improved knowledge.

Third, a complete and unambiguous description of the product and related processes must be provided to allow concurrent engineering to take place. The meaning of "complete" and "unambiguous" will be determined by the stage of design. A description that could be considered "complete" during conceptual design may be incomplete and ambiguous during detailed design. One of the challenges of concurrent engineering is to begin performing design tasks earlier in the process when certain details of a design are more flexible than they would be in a purely sequential process.

Finally, there need to exist a baseline product and process evaluation. This can be either a single product or process which is considered the best available (or "best-of-breed"), or some theoretical combination of systems which is deemed achievable within the projected envelope of technologies.

C.3 Component 3 — Required Capabilities

Component 2 function implementations require capabilities listed at Component 3. These capabilities are present in most engineering processes, but concurrent engineering places a unique set of requirements on them.

C.3.1 Data Definition and Capture, Design Synthesis, Trade-off, and Validation

Early, complete, and continuous understanding of customer requirements and priorities requires ready access to knowledge and data and interconnections between sources of knowledge and data not currently available. This understanding has two principal elements:

- the capture of historical data, and

- the capture of data on new designs, tools, methods, and materials.

To reach the required understanding of customer requirements and priorities through this data capture requires capturing the detail data on comparable products and processes, as well as their field support experience. Typically, knowledge of this data resides in the heads of a very few highly skilled, experienced people. Thus, "capture" means not only the acquisition of detailed data but intelligence (artificial or natural) that would allow ready access and review of this data by both highly skilled as well as less skilled people. The cost of achieving this without imposing some structure on the data and associated intelligence would be prohibitive. Thus methods of structuring or compressing data are supportive research issues.

Of course, in order for the data to be captured, it must exist or be discoverable. A significant required capability, therefore, is the set of mechanisms which generates the historical data necessary to concurrent engineering. An example would be mechanisms for generating feature-by-feature reliability and maintenance data on weapons systems in ways that are not used for manipulation for non-engineering purposes (for example, budgetary purposes).

Similar statements are appropriate for the definition of data on and synthesis of new designs, tools, methods, and materials. But it can be argued that the prime purpose of intelligence (again, perhaps artificial) in the capture of new designs is to allow the integrated translation of the new requirements into all aspects of the design in a concurrent manner.

The real goal is to allow visibility into the trade-offs and to examine the constraints in a larger context which includes product and process issues, manufacturing as well as field support issues. This improved visibility further supports a continuous review process which includes everything from design validation to more efficient management of the entire weapons system procurement cycle.

The availability of such tools would offer a more flexible procurement system, with shorter concept-to-deployment time, with greater visibility into the process for the designer,

manager, and procuring agency as well as providing all the supporting data to the various concerned parties.

C.3.2 Information Management, Dissemination, and Delivery

The management, dissemination, and delivery of product, process, and support information become a somewhat more complex problem in a concurrent engineering world than in current practice. Managing engineering data is difficult in the presence of integrated and continuing participation of multifunction teams in the design of product and processes. The requirement for flexibility to evolve the engineering, manufacturing, and support processes places an added burden on data management. This burden is increased by two factors: widely distributed teams and the size and complexity of weapons systems. Another function placing requirements on the product, process, and support data management capability is that of open and continuous communication between customer and vendor. All of this indicates a need for evolvable, tailorable, interoperable, secure, distributed, high performance enterprise information management systems. A discussion of the building blocks for such systems is in the section on Component 4 under the heading *Information Frameworks*.

In particular, within the management of engineering and production information there must be intelligent oversight for impact assessment of changes and proactive availability of designs. In the ideal design process, every change should be evaluated for impact on all functions and the cost of the entire life cycle. In practice this is difficult to assure. Within concurrent engineering, change evaluation is enabled and encouraged by the continued multifunctional team approach. Even then, systems must be introduced which assure that evaluation. There are two steps to that assurance. First, there must be an intelligent oversight to assess the impact of changes. This assessment can be based on models of product performance, manufacturing process (including schedules) and cost. Examples of such models are provided in the *Tools and Models* discussion (Component 4).

Second, to assure attention to changes and assessment of their impact by the relevant functional responsibilities, there should be a proactive availability of these designs to various functions. For example, if one individual makes a design change in the product, another person, who has designed the process, should not only have access to that change, but also be formally notified that a change has been made that affects tooling (or other process elements) in some way. Further, the latter individual should be required by the system to formally assess the impact on tooling design and tooling cost, and either change the design accordingly or provide suggestions for product design alternatives which minimize the impact on the various design objectives.

The capabilities described in the previous paragraph are examples of *policy enforcement*. Automated policy enforcement, tailored to the policies of each organization, can be implemented within the engineering information system. Ways of appropriately expressing organization-specific policies for such areas as change and configuration control, version management, methodology enforcement, timely notification, as well as others, so that generic mechanisms can enforce them, are now appropriate issues for advanced development.

C.3.3 Rapid Representative Prototyping

While modeling the product and process provides valuable knowledge of their performance and adequacy, at some point there must be a "first unit production" which creates the first physical version of the product. In many manufacturing enterprises, this first unit of production (prototyping) has several drawbacks. First, its production is usually slow and expensive, often requiring special tooling (both hardware and software) and perhaps interruptions of the current product's production system. Second, because parts are fabricated in tool rooms and job shops or on current production lines, the accuracy of prototype parts may be much better or much worse than those ultimately achieved when the product is produced in volume on machines and tools created specifically for this product. As a result, the prototype is often not representative of the quality which will eventually be achieved in production.

These difficulties often lead to delays and added expense in the iterative design process and invalid decisions based on prototype testing. One way to combat such problems is to achieve linkages between design systems and manufacturing systems which rapidly create representative prototypes. Some of the necessary capabilities include:

- feature-based design representations incorporating features which have manufacturing meaning;

- easy (perhaps automated), quick transformation of design descriptions into hard and soft tooling or software;

- flexible machinery and fixturing which allow an inexpensive and rapid changeover from current production to prototype production; and

- task level programming of manufacturing devices, including numerical control machine tools, robots, and inspection systems.

These capabilities, taken as a whole, with the integration of the appropriate intelligence, data structures, and communication systems, could provide a system which automatically transforms feature-based designs into task-level manufacturing programs and rapidly delivers them to the manufacturing floor for production of tooling, fixtures, and representative prototypes.

C.3.4 Process Robustness

Robustness can be thought of as the insensitivity of the product quality to product and process variability introduced either intentionally by design changes in product or process, or unintentionally through *noise*, such as drift in process or external factors the manufacturer cannot reasonably control. Product changes may include the production of a variety of models over one line or the continual improvement of product design.

Noise may include such factors as temperature, humidity, or variability of human performance levels. In any case, it is desirable to minimize the variability of the units produced by making the process insensitive to changes.

C.4 Component 4 — Technical Building Blocks

Component 4 consists of the technical building blocks necessary to create the capabilities described in Component 3. These include foundation concepts and underlying technical knowledge of the design system's hardware, software, processes, and management. They are grouped into five areas: data, information frameworks, tools and models, manufacturing systems, and design processes. Most of the technical areas listed in Component 4 both support and are required by multiple capabilities in Component 3. The technical building blocks of Component 4 are shown in Figure C.3.

COMPONENT 4

TECHNICAL BUILDING BLOCKS

DATA

Operational and support processes and environments data

Design process data

Manufacturing process data

Information architecture (model)

INFORMATION FRAMEWORKS

Enterprise information management system (including information architecture)

Information distribution system

Requirements, specification, design, and description languages

Requirements and specifications metrics

Simulation framework (including analysis of results)

TOOLS AND MODELS

Product, process, performance, and support models

Assembly models

Solid models

Cost models

Tools for analysis of simulations

Design rules that integrate performance and all the "ilities"

Problem identification and solution techniques

High performance computers

MANUFACTURING SYSTEMS

Integration of design systems and manufacturing cells

Production process technologies

DESIGN PROCESSES

Design team dynamics

Figure C.3. Conceptual Framework Component 4

Component 4 contains many building blocks that have yet to be organized by priority and by horizon (near, mid, and long term). The next phase of the study will include such an organization.

C.4.1 Data

The Data Area describes the specific kinds of data required to create and evolve the Component 3 capabilities. This area can be viewed in several dimensions including: life-cycle phase (concept, design, manufacturing operation and support, disposal), requirement attributes (performance, cost, time/schedule factors), time (existing, new), and product (F16, SS21, LHX, etc.). For example, to evolve the Component 3 capability to *capture data on comparable products, processor, and support* for use in concurrently designing a new fighter feature, one would need, among other things, maintenance cost and time data on similar features in existing, similar products.

One way to organize the effort to start capturing this data in usable form (as well as the efforts to develop the policies, procedures, and technology related to the capture and maintenance of the data) is to develop first an architecture for the information conveyed by the data. Without an information architecture (sometimes referred to as an information model) commonly accepted by all the services and support industry, a designer will not have sufficient confidence in the data to use it in making design trade-offs. The information architecture (or *information model*) has the effect of defining a common mapping between the syntax and semantics (i.e., the form and meaning) of the information. In this way, the many people developing the information and the person using the information have a common description of the meaning of the information. Since face-to-face interaction between the information developers and the information user is unlikely, there must be such a preordained common information architecture (model).

This architecture must be more than a dictionary in that it must employ an organization that allows for aggregation of information into (perhaps overlapping) classes and must allow for (perhaps classed) relations among classes and pieces of information. Otherwise, the process of arriving at a consensus will be extremely inefficient and will probably fail. A non-aggregated or *flat* architecture is almost impossible for people to understand.

It must be understood that such an architecture is not a data model. A *data model* is concerned with the organization of the data within the computer system in order to support efficient query and update of the stored information.

This architecture must be evolvable to allow for the addition of new classes and modification of existing ones. In this way, the architecture can be developed and used in parts rather than requiring completion prior to use. The same characteristic that allows the architecture to be evolvable also allows it to be extendible and tailorable. Extendibility and tailorability are necessary because the information architecture will be adapted in company-specific ways. For example, a particular organization's integration of design and manufacturing information may be based on a group-technology approach (as in the case of John Deere, Appendix A). This will drive part of the information architecture for that company but not necessarily for other companies or for DoD.

The process of arriving at consensus on this architecture will be difficult. The barriers are social and political rather than technical. In order to integrate the engineering effort, the

parts of the architecture for different specialties (for example, electronics and structures) must proceed from a common vision of the architecture and must be represented in a common format. In parallel with the architecture development, the policies and procedures for capturing data must be developed, reviewed, and established. Once parts of the architecture have been set and relevant policies and procedures are in place, the data to fill in those parts can be gathered.

C.4.2 Information Frameworks

The second area of building blocks is that of information frameworks. An *information framework* (hereafter, simply *framework*) is a structure for establishing, storing, executing, and evolving information-based policies and tools. Within a framework, there are usually capabilities to organize, access, and evolve the data used by the policies and tools. Using a conventional or standardized framework that has been designed for evolution and tailoring allows for easier interaction among tools, among engineers, among teams, and among organizations.

Such a framework is itself not a physical system but rather a set of standards and specifications. This allows a marketplace for systems to develop such that the systems all share the attributes set in the standards and specifications. At the same time, the physical systems may be tailored to specific applications or organizational needs, may be relatively larger or smaller, and have all the other characteristics of being available in an open market. Furthermore a framework-based approach allows for competitive tools to be developed for specialized aspects of the engineering and production problems. Also, since the framework is extensible and evolvable, completely new classes of tools and information can be accommodated into systems built to the framework specifications. An analogy is the common household electric drill. First, a drill is built to a specification that is consistent with conventions and standards for drill bits. There are tremendous economies gained from the fact that a special drill for each bit size does not need to be bought. Also, there are economies realized from the fact that bits from one supplier fit other suppliers' drills. Another part of the analogy is that compromises exist in the generality of the specifications: there are 3/8-inch drills and 1/2-inch drills each supporting its own set of available bit sizes. One should expect and allow such compromises with automation frameworks as well. Still another part of the analogy is that the user of a drill can be faced with a cost-effectiveness decision on whether to use an integrated tool such as a sanding disk or whether to buy a special-purpose, non-integrated tool such as an electric sander. For some classes of automated tools, this phenomenon should also be expected but it can be mitigated by allowing tools to be attached to the framework via a well-defined interface. This also allows an evolution path from the current situation where DoD suppliers buy non-integrated tools and pay for their *ad hoc* integration or are forced to buy a vertically integrated package from a single vendor and become captive to that vendor.

No company would buy a drill requiring non-standard bits without a very serious cost-effectiveness evaluation. Yet it is remarkable that contractors' standard practice is to buy non-integrated, standard-purpose, automated CAD, CAE, and CAM tools with non-standard, proprietary interfaces and furthermore, that they have not effectively banded together to force the creation of frameworks for the support of the required standard interfaces.

Each major DoD weapons systems is designed and built by large numbers of organizations. It is clear that concurrent engineering places a relatively large burden on the systems which manage enterprise information and the automated tools that use that information. Without conventional or standardized frameworks for this purpose, DoD will repeatedly incur the costs of integration of its suppliers' data, object, and knowledge bases. This expense will include the costs of evolution of information systems not designed for evolvability, for repeated solution of the problems of integrating design and manufacturing information systems, and for repeated transformation of data and knowledge bases to the formats required by the information systems of second-source vendors.

The general notion of information frameworks is connected to the ideas expressed in the previous remarks about data. The information managed by a framework for the engineering and production enterprise includes the data described in the previous section. Therefore, the information architecture described above can and should be used as an organizing factor in the enterprise information framework. This allows the common understanding about the syntax and semantics of the information that is required among the developers of the information (for example, the maintenance organizations) and the users of the information (for example, the design engineers) to be embodied in and facilitated by the enterprise information system. This system can facilitate the required common understanding because it realizes the standards and specifications of the framework including the common information architecture or model. Further details on frameworks can be found in the appendix on methods and technologies.

The idea of enterprise information frameworks is not new and there are efforts which claim to be addressing the technical problems arising in the discussion above. This itself raises a significant DoD issue. The technology working groups that met at the workshops leading to this report very strongly recommended that DoD assist in the creation of standard frameworks for computer aided engineering, manufacturing, and logistics. There are, however, several efforts, usually differentiated by engineering domain of the sponsors, all addressing this problem and yet not proceeding from any sort of common vision that we can discover. These include systems driven by the needs of airframe specialists, electronics specialists, logisticians, and software engineers.

It is very important that DoD integrate the vision of these efforts. DoD, its supplier industries, and the CAD/CAE/CAM/CALS hardware and software vendors must make sure that the common vision be based on ideas chosen for their technical merit and their achievability rather than on the basis of the political capabilities of their DoD advocates. It will take a commitment and involvement of high-level DoD and industrial management to ensure this. Otherwise, DoD and its suppliers could waste a great deal of money (hundreds of millions of dollars) addressing the frameworks issue in the wrong way. The CALS initiative office intends to address this problem.

C.4.2.1 Information Framework Building Blocks

Within the area of frameworks and in addition to the considerations discussed previously, there are several, more detailed technical efforts that should be undertaken. The order of discussion of these does not imply a priority mapping of them; such a mapping is yet to be done.

One of the framework areas needing further research and development has to do with languages that capture requirements, specifications, designs, and product descriptions. These languages are likely to be application domain specific (for example, specific to electronics or, perhaps, analog electronics). They are also likely to be intended use specific (for example, specific to product description). An example language with great promise is the VHSIC (Very High Speed Integrated Circuit) Hardware Description Language (VHDL). This can be used to describe the function, behavior, and structure of electronic circuits and potentially can be linked to physical descriptions, for example in the language EDIF (Electronic Design Interchange Format). If this idea could be applied to the mechanical and other engineering domains, many benefits would ensue. For example, a separation between technology-dependent and technology-independent design characteristics could be made. Also, the intent of the top-level designer might be easier to capture in the flow down to the detail designer. These, in turn, would make technologically upgraded reprocurements easier and less risky.

Another example language would be one which captures an unambiguous, complete product description that can be passed among product and process designers and then on to production facilities and the customer for archiving. Such a language might incorporate other, domain-specific languages like VHDL. It appears that PDES is intended to be such a language. PDES is discussed in Appendix B.

The connection between languages and concurrent engineering relates to several of the Component 3 capabilities. Requirements and specification languages have the potential for decreasing the cost and increasing the effectiveness of complex trade-off analysis by encouraging less ambiguous requirements and specifications. Further, they hold the promise for increasing the automation of the mundane part of the design effort. By making the design cycle dramatically more efficient, the added complexity of bringing the many downstream considerations to bear on the design becomes much easier. Also, if partially automated synthesis is achieved, then it becomes far easier to enforce design rules that relate to production, maintenance, reliability, etc. An example of automated synthesis from a language description is happening in the integrated circuit domain where so-called silicon compilers are being developed to translate behavioral descriptions in VHDL into tapes that directly drive the fabrication process. Having a language description of a design and a language description of a specification adds to the possibility of increasing the accuracy and decreasing the cost and time of design validation. Finally, the existence of such languages changes the way that interelated design and downstream information gets delivered to the DoD and maintained for future use.

Within the context of requirements and specification languages, the technology working groups in this study raised the issue of the adequacy of existing metrics for requirements and specifications related to downstream processes. It was felt that adequate metrics for product performance exist but that adequate metrics for reliability and maintainability do not. In this case, "adequacy" refers to usefulness in making design trade-offs. Thus, it has been asserted that measures such as mean time between failures and mean time to repair are not sufficient for doing detailed design trade-offs. The same sort of statements could be made about producibility metrics.

Another part of a framework for managing enterprise information is the information distribution system. These are the mechanisms that provide notification of engineering,

production, or design changes to the appropriate people, including other designers. The information distribution system is the building block that provides the capability described at Component 3 under "Information management, dissemination, and delivery" as "proactive availability of ... designs." The information distribution system can be viewed as the set of mechanisms that enforce the policies set by organizations. Enterprise information frameworks should have the general capability of executing the policies set by organizations. A policy here is simply a set of actions that must occur in case some event occurs, for example notification of appropriate engineers in case a design change occurs. In order for this to happen, development work and perhaps standards development need to be pursued on how to represent policies in an automated framework and how to implement generic mechanisms that will execute whatever policies an organization sets. The importance to concurrent engineering is that the complexity and integration of DoD systems demands, at the same time, both large numbers of engineers and a great deal of cooperation among them. Concurrent engineering increases the burden on this integration of effort over a distributed enterprise information framework.

A special-purpose framework for simulations has been suggested as very important to the concurrent engineering process. To make the synthesis and comparison of designs more efficient and at the same time expand the scope of the target optimization function to include more downstream processes, companies building complex products increasingly depend on simulation. The same argument applied to generic enterprise information management systems and the requirement for frameworks applies to simulation systems as well. There would be large increases in the efficiency of generating new simulations if simulation frameworks were in place. If these frameworks (not the systems themselves but rather the specifications and services provided by the systems) were standardized, then the government could easily receive the results of simulations and, more importantly, the simulation models of the products as deliverables. In this way, the government could compare competing designs, make underlying assumptions visible, and use the simulation models in planning and reprocurements. Without a simulation framework in which the simulations reside, the government must pay for the development of whole new simulations and procure unique support hardware and software for each simulation built. Also, because many factors affecting the simulation are buried in the unnecessarily unique code of each simulation, the DoD cannot reliably compare simulation results. The need for standards related to simulation models was expressed, for example, within AT&T where it was found that the existence of several ways of building simulations was causing an inability to get the simulations to work together. An example of a simulation framework is the Strategic Defense Initiative Architecture Dataflow Modeling Technique Simulation Framework.[95]

A common problem with simulations is that their results are so voluminous that people cannot adequately analyze them. Concurrent engineering will make this problem worse because it causes an increased use of simulations and the simulations themselves cover a broader spectrum of information. Thus, any framework for simulations must allow for the

95. Linn, J.L., et al. *Strategic Defense Initiative Architecture Dataflow Modeling Technique, Version 1.5*, IDA Paper-2035, Institute for Defense Analyses (Alexandria, Va.), April 1988.

tools for the analysis of simulation results.

C.4.3 Tools and Models

As designs evolve, it is important that the designers have tools and models which apply known rules of thumb for such things as manufacturability, evaluation of the design's "goodness" as it relates to functional objectives, estimation of product and process performance and cost, and projection of the impact of changes from one alternative to another. To do so, a broad array of empirical, simulation, and analytical models must be provided in a computing environment with sufficiently high performance and ease of use to allow affordability and usability to the manufacturing enterprise.

C.4.3.1 Process Models

To assess the impact of various product and process changes or alternatives, it is desirable to provide models of various manufacturing processes, such as metal cutting, forming, injection molding, casting, soldering, etc. Ideally, these models should provide the user the opportunity to alter easily the product geometry or process parameters interactively and through various engineering, geometric, statistical and scientific analyses, provide an accurate projection of process performance. This performance should be measured in terms which directly relate process performance (such as speeds, temperatures, and accuracies) to product measurement (such as tolerances, material integrity, strength, and surface finish). These together can provide an assessment of product cost, performance and reliability without ever having produced a product. Further, if these models are based on actual measurements of real production systems for this product or similar products, they will allow accurate assessments of impact of product and process changes in the company's actual production facilities.

C.4.3.2 Assembly and Cost Models

A number of systems exist for the evaluation of the "goodness" of assembly designs. These provide some level of cost prediction and a guidance tool which directs the designer towards design options that are more easily assembled based on heuristic rules of thumb regarding design for assembly. Others have developed cost models based on specific geometric models of position and path which must be executed by a human or robot in order to accomplish the desired assembly. Both modeling concepts have great value and promise for improving the design for assembly. In the concept of concurrent engineering, it is important that these models be linked together with models of the fabrication process so that cost is not simply driven from assembly operations into the fabrication operations of component parts. This integration of model and projections should be accomplished through the generation of cost models.

C.4.3.3 Manufacturing System Models

Most of the process, assembly, and product models assess the capability of the product and process to perform at a certain level with a certain reliability. It is also important to assess the capacity of the manufacturing system, that is, its ability to produce a certain number of products at a certain level of capital equipment and human (production manning) investment. These "flow models" of manufacturing systems may either take the form of analytic or simulation models. Analytic models have been derived for simple systems of multiple machines, fixtures, personnel, tooling, and material handling systems. However, as

manufacturing systems become more complex, it is often necessary to either employ heuristics derived from analytic models or to create simulation models which allow a greater complexity in their construction.

Integration of capacity and capability models in manufacturing becomes more important as designers extend the capability of manufacturing systems to provide an extremely small, extremely accurate, or extremely high strength products, thereby challenging the capabilities of manufacturing systems. A trade-off begins to emerge wherein the designer is forced to choose between process yield and product performance. This is especially true in the electronics industry, where increased levels of integration provide higher performance of electronics systems yet drive production yields lower. As yields diminish, they force a linkage of the capability (yield) models of processes to the capacity models of production flow. This is not only because of lost production volumes due to lower yield, but also due to the need to recycle components through previous operations in order to repair or rework. This requires a whole new approach to modeling the manufacturing systems which incorporates reliability and statistical yield analysis with capacity and flow analysis.

C.4.3.4 Design of Experiments and Other Statistical Methods

As industry continues to search for improvements in quality and productivity through the implementation of programs such as concurrent engineering, the discipline of statistics will play an increasingly important role as, for example, *signals* for potential improvements become smaller relative to the *noise* in the systems. Accordingly, research in applications ranging from graphical display of data, through design of experiments, to the application of time-series analysis in complex, feed-forward and feed-back systems will be needed.

Additional statistical tools that support process improvement and robust design include modern statistical graphics, exploratory data analysis, and time-series analysis. Establishing processes that are robust to external disturbances and simultaneously responsive to control requires multivariate considerations of error transmission and parameter sensitivities. Research in applications should include quantification and verification of expert prior knowledge to enhance managerial decision making, statistical studies in non-linear estimation, finite element analyses, and stochastic disturbances in dynamic systems. Investigations of technical topics such as optimal estimation of dispersion effects, variation transmittal, detecting dispersion effects in unreplicated factorials, simplifying transformations, and technology-domain-specific models will also continue to be important research areas. As signal-to-noise analysis and orthogonal array techniques become more widely used, extensions, refinements, and increased efficiencies should be explored.

In addition to research, the DoD and its contractors should take advantage of existing statistical tools. These includes statistically designed experiments: split-plot designs, sequentially applied designs, designs subject to constraint, designs constructed from incomplete blocks, response surface designs, bits and pieces of mixed-level fractionals, designs to fit and validate models, and designs robust to time-dependent correlations and non-homogeneous error structures.[26] These experimental strategies are widely used in the

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agricultural, medical, and chemical industries. Use of these methods can contribute to the improvements that are sought through concurrent engineering.

C.4.4 Manufacturing Systems

Besides the understanding and modeling of manufacturing processes and systems described in the Tools and Models section above, there are important systematic building blocks and understanding which relate to manufacturing systems which must be provided to achieve some of the required capabilities of Component 3. In particular, the rapid prototyping and process robustness capabilities described in Component 3 will require integration of the design systems in manufacturing cells and systematic techniques for acquiring and analyzing empirical data which statistically describe the capabilities and capacities of the manufacturing systems. (In addition, these specific capabilities of Component 3 also require many of the building blocks described in earlier sections relating to data, frameworks and tools and modeling.)

C.4.4.1 Flexible Manufacturing Cells

To provide a responsive environment which lowers the time-to-market of new products and time-to-delivery of current products as well as providing rapid and representative prototypes, there must be a heightened level of flexibility on the manufacturing floor. Efforts have been under way for some time to achieve higher levels of flexible automation, especially in the areas of material removal, assembly, and inspection. To link these computer controlled devices more effectively to the design systems and more quickly and accurately derive the requisite control programs, it is necessary first to automatically transform design descriptions into manufacturing processes and control programs. Ultimately, there should be a "next generation controller" capable of receiving only product descriptions and automatically interpreting that description and turning it into the machine motions and control points necessary to achieve the desired product geometry, tolerances, and material specifications.

C.4.4.2 Production Process Technologies

The aggressive pursuit of advanced technological products requires that there exist manufacturing technologies able to produce such products. New technological developments are necessary in such areas as composites processing, semiconductor manufacturing, and ceramic materials processing. While it is not the focus of this report, these critical production process technologies affect the ability to perform concurrent engineering to the extent that their lack of development overly constrains the design process.

C.4.5 Design Process

All of the four categories of technical building blocks described above are groups of tools, knowledge, and environments which provide some element of, or support to, the engineering process. While all are essential to achieving the promise of concurrent engineering, it is also desirable that we develop an improved understanding of the design

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96. This discussion of statistical methods was provided by Prof. G. Rex Bryce, Professor of Statistics, Brigham Young University.

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process itself. There are aspects of the design process, as typically practiced today, which inhibit the attainment of the goals of concurrent engineering. These relate to the process of design synthesis by the individual and group, and the psychological and sociological phenomena which play out in the execution of a team design process.

For example, it has been observed that design teams have an unrealisticly high priority on the early selection of one alternative design concept, rather than allowing a state of uncertainty to exist for a longer period of time, a state which is necessary if a full evaluation of alternatives is to be completed. Although the evaluation of alternatives might better have continued longer, many design teams will grasp an alternative, develop analyses which support the chosen concept, and defend it unreasonably. There are a number of psychological, sociological, managerial, and acquisition process elements which support this overly high priority on early selection of design concept, and the dogged defense of the concept even when it might be improved. Further study of these phenomena and motivations is desirable so that they can be improved or overcome through the development of various design tools, procedures and policies. This understanding would also allow teaching of better concepts for design synthesis, especially within the team-based design process.

D. CONCURRENT ENGINEERING AND THE ACQUISITION PROCESS

D.1 Introduction

Concurrent engineering seeks to increase quality, reduce cost, and decrease development time. It seeks increased efficiency and effectiveness through continuous process improvement, the elimination of non-value-added work, and practical optimization of the system consisting of the product and its manufacturing and support processes. In the past, the DoD attempted to achieve these objectives in a piecemeal manner. These individual efforts spawned "stovepipe" organizations with their attendant regulations, specifications, and standards. These efforts were frequently successful in their target areas, but were unable to achieve simultaneously the three objectives of increased quality, reduced cost, and decreased development time.

Concurrent engineering seeks to achieve these objectives simultaneously by truly integrating diverse specialities into a unified development process. This approach has important implications for the DoD acquisition process. The following discussion addresses the implications identified during this study. It is structured around generalizations of reported practices in today's DoD acquisition process and offers potential alternatives.

D.2 Specifications

Fundamentally, a specification is a series of requirement statements which are quantifiable and verifiable. Collectively, specifications can be viewed as a tree, with a Type A specification being the trunk, Type B the branches, and Type C the leaves. The development processes begin with a "Type A" systems specification that states the technical and mission requirements for a system, allocates requirements to functional (performance) areas, documents design constraints, and defines the interfaces between functional (performance) areas.

Several "design-to" or "Type B" specifications are normally developed from the Type A specification through a series of systems engineering trade studies. The Type B specifications state the performance requirements for the design or engineering development of each configuration item. The specifications are sufficiently detailed to describe effectively the expected performance characteristics of the item.

As development nears completion, "Type C" (Part 2) or "build-to" specifications, are developed. In addition, while each program has its unique set of A, B, and C specifications that define its mission needs and constraints, these program documents also incorporate many government standards and specifications which define items, approaches, procedures, or testing to be used in the development and production process. These government standards are used so that new programs may benefit from lessons learned, commonality is promoted, and logistics costs are minimized. There are more than 40,000 military specifications and standards whose average age is 11 years (technology currency). Their combined effect is to impose premature and not well understood constraints on contractor activities.

In some cases, military standards and specifications consist of detailed test and inspection procedures, or manufacturing processes which contractors must follow exactly for their product to be accepted by DoD's auditors. The test, inspection, or manufacturing processes on which the specifications were based, however, are frequently obsolete even

before the contract is approved. Such "how-to" specifications tend to place conformance to canned processes ahead of all other requirements, including those of the users. Many such specifications are imposed on a blanket basis without any true understanding of their effect on the engineering effort. A contractor's compliance with the letter of these specifications becomes the DoD's primary measure of contractor performance. As a result, contractors view such compliance as the lowest risk approach to engineering management. Since program managers usually reject alternatives or enhanced processes in favor of the specified tasks, contractors have little incentive to improve beyond the specified process. Similarly, potential bidders who propose alternatives run the risk of being found "non-responsive."

In many cases, program-specific and generic specifications are enforced as ceilings to be reached (hopefully) at program maturity rather than as floors from which improvement can begin. This motivates the contractor to work his trade-off processes downward from the ceiling rather than upward from the floor. The contractor is discouraged from approaching the specified ceiling because such effort decreases the prospect of showing "substantial improvements" later in the program. Such "substantial improvements" in later phases may lead to additional contract funding.

Although the original intent of many of these specifications was to provide a common baseline for accelerating the development of improved methods and processes, rigid adherence and strict enforcement has had the opposite effect. The standards now serve as a common denominator of mediocrity. Government specialists whose role is to monitor contractor progress become enforcers of the specifications. Problems are often "solved" by adding more enforcers and auditors.

Contractors need the latitude to improve the manufacturing processes and procedures if DoD is to improve the efficiency and effectiveness of the acquisition process. One method of institutionalizing this objective is to emphasize the program-specific (Types A and B) specifications over general standards. General "how-to" standards should be referenced as baseline guides rather than as absolute requirements. In this way, they can be a source of lessons learned and a reference for contractor processes. The contractor should be required to describe any proposed process and to provide supporting documentation demonstrating its effectiveness. The contractor should explain how the contract will be managed, including the critical control points.

The program office should be allowed to impose a process only if its superiority over the contractor's process, in terms of cost or quality, can be demonstrated. This requires that both the contractors' and government's engineering personnel understand their processes and process management. Neither can be a passive observer. The program-specific specifications should be in a form such that "blanks" are provided for both the proposed quantitative performance characteristics and the superior processes. Appendices to these specifications should provide guidance and lessons learned for the tailoring process. The form of the specifications needs to be studied prior to the initiation of each program phase so that the appropriate trade-off studies can be accomplished in a timely manner to quantify the requirements.

This is not to suggest that simply deleting all the "how-to" specifications will produce the desired results. Some other means to manage risk and measure contractor performance are

necessary. Approaches to such risk management and preformance measurement are discussed in the following paragraphs.

D.3 Fragmentation in the Specification

The "ilities" evolved in response to actual or perceived needs that once were not being addressed. As each "ility" matured, a separate terminology evolved, and accepted mathematical analysis procedures became institutionalized. The need for proficiency in these procedures and terminology led to specialization. This, in turn, caused "stovepipe" functional activity by the contractors as well as the government.

Typically, an "ility" is institutionalized through a military standard and contractually implemented through assigned tasking in the statement of work (SOW) portion of the contract. It has an associated budget and requires delivery of a product, usually a report. The standards on which the SOW tasking is based describe generalized management procedures (as opposed to engineering functions) that are similar from "ility" to "ility" and often duplicative (e.g., four deliveries of Failure Effects Mode Criticality Analysis). The SOW tasking generates activity that is indirectly related to the derivation of essential product characteristics.

An alternative approach is to define the product characteristics that the "ility" seeks to influence and include them in the specification. The general rule is, if a characteristic is important, then it should be in the specification. To be in the specification, it must be quantifiable (stated in performance terms), and verifiable. This approach would ensure the appropriate top-down requirements process through the specification tree.

Consider, for example, if producibility and unit production cost are treated as part of the specification:

- Recognize cost (unit production cost) as a technical characteristic in the specification.

  Rationale: A better weapon system which is unaffordable does not support the objective of achieving "Best Value" for the user and the tax payer. Cost is a legitimate technical constraint on design, driving both technology selection, and producibility and supportability considerations. Producibility and supportability considerations become effective requirements when they are quantifiable and are administered in a top-down, requirements driven process. Consequently, these requirements must be developed within the context of cost constraints.

- Require capable manufacturing processes in the specification (a process capability index).

  Rationale: Traditional military specifications and standards on manufacturing processes and workmanship have an objective, to define minimum standards for these processes. They are "how-to" documents. As such, they do not encourage innovation and improvement. Process capability indices (such as C_p and/or c_{pk}) are an alternative to the traditional military specifications and standards. Such indices provide the same assurance of stable manufacturing processes with an agreed-to variability and/or a variability reduction effort. They give

the contractor the latitude to improve the processes. In addition, the capability indices address the relationship of the specification to the variability of the process. Process capability indices are both producibility and quality requirements.

Most but not all of the "ilities" characteristics may be treated in a similar manner. Qualitative characteristics that can not be expressed in quantifiable terms require extensive interaction with users, are major areas of uncertainty to a program, and in many cases have led to inefficiencies in the acquisition process.

D.4 Focus on an Integrated Development Process

The contractor and DoD must reach mutual agreement on the general nature of development processes if some of the guidance and constraints within the traditional military standards are to be subject to tailoring and streamlining. This agreement should focus on a structured development process emphasizing time-phased sequence of tasks, mutual understanding, and discipline. Prerequisites to such an agreement are as follows:

- Deriving realistic systems requirements from the users' intended applications.

- Understanding operational use and environments.

- Understanding manufacturing processes and materials.

- Understanding failure processes and their relationship to manufacturing and service induced flaws and defects, material usage, and environmental sensitivity.

- Understanding support processes.

- Establishing product and process design criteria based upon application.

- Designing use and manufacturing process capability (designing to the quality level that can be controlled in manufacturing and maintenance).

- Characterizing the design through material and process characterization, analysis, and testing.

- Optimizing the system of product and processes in a systematic, phased, and practical manner.

The structured development process would include the following activities:

- Qualify product together with the manufacturing processes by Milestone III.

- Control the manufacturing and depot/field maintenance processes to the level addressed in product and process design.

- Monitor actual use and adjust life management based upon deviation from initially projected use and environments.

- Monitor and improve the manufacturing and depot/field maintenance processes.

The above list constitutes a generic description of an integrated process that is responsive to the objectives of the concurrent engineering. These activities are practiced in some areas of the DoD acquisition process.

D.5 Specification Requirements (Section 3) and the Verification of the Requirements (Section 4)

There are two principal sections to a development specification: Section 3, "Requirements," and Section 4, "Verification/Qualification Requirements." Each line item in the requirements section must have a corresponding line item in the verification section. A requirement is not effective if it cannot be verified. There is no discipline if the verification actions are not timely.

The Section 4 verification line items should describe tasks, schedules, and success criteria. The tasks should be representative of items found in D.4, in the list of the nine prerequisites. However, Section 4 requirements should not be summarily imposed on the contractor. They should be mutually determined during the contract negotiation process and would become the tailored "process" for satisfying the requirement (see Section D.4).

The proposed approach provides a tailored work package for all of the essential product characteristics in each of the specifications which were negotiated between the program management office and the contractor. These packages would provide the basis for developing program cost and schedules as well as performance-based progress criteria. They would be documented in an appendix to the specification as a Systems Engineering Master Schedule. The agendas of all technical reviews should be developed around the performance-based progress criteria identified in the verification sections of the specifications, as should contract progress payments.

The mutually-defined, time-phased verification actions contained in the Systems Engineering Master Schedule provide the means for risk management of contractor progress. They are comparable or superior to those currently provided by the system of military specifications and standards.

D.6 Relationship of the SOW to the Specification and the Integrated Deliverables

The SOW should define the work effort required to implement the program successfully. In effect, the SOW should implement the necessary tasks identified in Section 4 of the specification. Current SOWs call out work packages in a manner that is decoupled from the specification requirements. This practice accentuates the separation among mainline engineering, specialty engineering, manufacturing, and field support. Concurrent engineering is frustrated when independent "stovepipe" activities are encouraged through the SOW.

The SOW is also used to define the Contract Data Requirements List (CDRL) items. In effect, these items represent written reports of functional activities. The contractor must prepare and deliver CDRL items. They are independent of the integrated product described in the specifications.

Three types of contract data are used in the technical management of programs: (1) perishable data provide information needed to accomplish the task but will not be needed in the future, e.g., status reports; (2) historical data reflect program details required to manage the program, but will not be needed after development is complete, e.g., test reports; and (3) permanent data permit the support organization or a user to accomplish their mission and

will be needed in the future, e.g., engineering drawings and technical orders. Where possible, CDRL items should be limited to "permanent and/or historical data." Contractual arrangements should be made to allow government access to the working data, in the contractor format, for perishable and historical data.

D.7 Requests for Proposal and Source Selection

Prime contractors, who will be responsible for the overall product development phase, are typically selected in a competitive process called source selection. The information evaluated during the source selection is provided by one or more offerors in response to an Request for Proposal (RFP). The RFP includes model specifications, statements of work SOWs (Section C), instructions to the offerors (ITO) (Section L), evaluation factors for award (Section M), and other sections as appropriate.

In the traditional RFP/Source Selection Process, the offerors' responses to the RFP emphasize the non-contractual technical proposal, cost, and schedule. This occurs because the offerors perceive that to win the contract, they should respond to the government with the government-developed model specifications and SOW language. The non-contractual technical proposal contains the rationale for the superiority of an individual offeror's proposal. If contracts are awarded on the strength of the technical proposal, then offerors have no incentive to propose innovative solutions to the users' needs or implement improved processes beyond those described by the government.

An alternative approach is to build the RFP around performance-based specifications. Also, each offeror would bid detailed development specifications and a specification tree as described in the ITO. Each offeror would bid quantitative Section 3 characteristics, Section 4 verification tasks and schedules, as well as overall development costs and schedules. Detailed specifications may be left partially complete during early program phases, provided there is contractual agreement on when and how they will be completed. The evaluators of the offerors' responses would then have evidence of: (1) the offerors' understanding of the user's needs; (2) the specific character of the offeror's proposed solution; and (3) the quality of the contractually binding development and verification processes, tasks, and schedules.

During the source selection process, an offeror and the system program office must mutually define a bilateral agreement. The bilateral agreement would consist of the understanding of the systems (including processes) essential characteristics (Section 3 of the specification), the methods for verification and validation, demonstration milestones, and risk reduction activities to support the decision points (Section 4 of the specifications). The bilateral agreement would be integral to the specifications and will be contractual. Achieving the development objectives depends on the two parties coming to a mutual agreement (not dictated agreement) on the job to be done. The source selection must focus on the specification. The technical proposal would remain non-contractual.

The government should minimize the task-oriented engineering portions of the SOW. The SOW need only state that the offeror shall accomplish all work necessary to satisfy the specifications (requirements and verifications) and the schedules for the reason cited in D.6.

D.8 Performance-Based Progress Criteria and Risk Management

The verification tasks of the development specifications with supporting task schedules and success criteria should be the basis for performance-based progress criteria and risk management. This would provide the necessary management tools to put discipline in the systems engineering management process by establishing accountability and ensuring management involvement.

D.9 Development of Integrated Requirements for a New Product Development Activity

Sections D.2 through D.7 describe a set of integrated requirements. The quantification of the requirements (to assure that they are realistic, internally consistent and timely) depends upon the quality of the systems engineering process. This involves functional analysis, identification of trades and options, allocations, etc. Sections D.2 through D.7 show that concurrent engineering demands a systems engineering process broadened beyond functional engineering and requiring increased depth. The systems engineering process will have to be a team activity involving engineering, manufacturing, product support, and customer (the user, the maintainer, the trainer, and the program management office). Achieving the required level of teamwork is a demanding process which requires competent people with specific experience and understanding of the product line (aircraft, missiles, ships, tanks, etc), user, technology base, acquisition process, etc.

D.10 Integrated Acquisition Strategy

The full expanse of the contractual requirements, items, and conditions conveys to the contractor a set of priorities and an operating environment for a specific acquisition process. The primary objective of a proposed contractual process must be to create an atmosphere that encourages contractor innovation to achieve the "best value" (combat capability) of the DoD product to satisfy the users' needs within time and monetary constraints. Traditionally, the DoD has used Business Strategy Panels to review the proposed acquisition strategy. These reviews have tended to focus on contracting, legal, and fiscal issues. The sufficiency of the technical process and the timing of the reviews to make sure that the program will be ready to proceed to the next phase have not been major foci.

Business Strategy Panels should be restructured as Acquisition Strategy Panels. By focusing on all facets of the proposed strategy, technical as well as business considerations, they should ensure that the system being developed is designed to meet fully the users' needs. Acquisition strategies should ensure that the technical approach is a correct one and that it is reinforced by the business approach. The technical requirements, evaluation criteria, contract provisions, and all other elements that support the objectives of concurrent design must be integrated into the best strategy possible. Acquisition Strategy Panels should be multi-disciplined and should be structured to provide the advice of the best talent available in an open-minded environment.

D.11 Functionally Integrated Development Teams

The existing acquisition process encourages fractionated efforts by all parties involved. Concurrent engineering, however, requires the integration of the "ility" functions into the activities of the design, manufacturing and product support processes. The steps cited previously, (D.2 - D.9) establish an integrated set of requirements for each product

configuration item. The program management offices should establish a set of project-oriented multifunctional teams. Each configuration item/specification should be the responsibility of a specific team. These teams should include representatives of all applicable disciplines (for example, engineering, manufacturing, and acquisition logistics).

Historically, contractors' organizations have mirror-imaged their DoD client. The DoD can use the contractors' this tendency to encouraging industry adoption of this multi-functional team concept with team ownership of each configuration item specification.

D.12 Motivation

Performance-based progress monitoring provides a positive incentive for getting employees and management involved in establishing and meeting requirements. It should be used to motivate employees to surface problems and issues early as well as encourage them to develop innovative approaches to meeting the performance-oriented requirements of specifications. Incentive pay and promotions should be linked to performance-based progress.

D.13 Closure

The previously cited steps are intended as examples of how the concept could work within the DoD acquisition process. As such, there are many other facets that must be addressed. This report concludes that the proposed concepts can work, are practical, and that the DoD must assume a leadership role to make it happen. The advocates for the process should be the Under Secretary of Defense for Acquisition (USD(A)) and the Acquisition Executives of each of the Military Services. They must champion the essential technical processes if the objectives of the concurrent engineering initiatives are to be met.

E. CONCURRENT ENGINEERING AND ACQUISITION POLICY

E.1 Objective

The principal goal of the DoD acquisition process is to satisfy the users' requirements by efficiently and effectively developing and acquiring weapons systems. The President's Blue Ribbon Commission on Defense Management notes that weapons systems take too long to develop, cost too much to produce, and often do not perform as promised or expected. A refocusing of the acquisition process is needed to emphasize achieving the "best value" (combat capability) in DoD products. This means satisfying users' needs within time and monetary constraints. Concurrent development and qualification permits multidisciplined, timely tradeoffs to be made in pursuit of the optimum balance of capability, cost, and schedule. Concurrent engineering with its focus on practical optimization of the product and its related processes, instead of just the technical performance of the product could be a high payoff initiative in DoD's Total Quality Management and Could Cost strategies.

E.2 Application

To accelerate the application of concurrent engineering concepts, the DoD is committed, under the Total Quality Management (TQM) initiative, to a strategy for continuous process improvement. All processes, such as management, engineering, manufacturing, and support, must be included under TQM. Concurrent engineering is one means of implementing this strategy, specifically in the area of designing products (weapons systems) and the processes to produce and support them. It should apply equally to DoD and its contractors. By establishing an Interim Acquisition Policy, the DoD can take the lead in encouraging industry to apply concurrent engineering concepts. The elements in the following sub-sections are viewed as keys to the near-term implementation.

E.2.1 Interim Acquisition Policy

The focus of the Interim Acquisition Policy should be on the integration of DoD and its industrial base to improve quality, reduce cost, and decrease development time. It should address the following objectives:

1. The revitalization of the systems engineering process, extending systems engineering to include all aspects of quality, not just technical performance.

2. The integration of requests for proposals, elimination of segmented requirements from each specialty organization.

3. The integration of design reviews, structured according to specification trees instead of functional areas.

4. The application of performance specifications, rather than the myriad of detailed "how-to" procedural and process military specifications and standards. "Streamlining" should be revitalized.

5. The elimination of no-value-added effort. Statement-of-work tasks which dictate procedures and processes and specify deliverables should receive special attention. The "Could Cost" approach should be applied.

6.   The development of new DoD procedures and processes to enable DoD to satisfy its management responsibilities.

E.2.2 Near Term Education and Training

Policy implementation will require education and training. As a minimum, the Services should train a multidisciplined cadre at each product division. All acquisition personnel should receive awareness training.

E.2.3 Longer Range Policy Revision

This process should begin with the revision of DoD 4245.7-M, "The Transition from Development to Production." This single document addresses the technical development process from start to finish, from design through manufacturing and support. Many things have changed since the current document was developed. Then, on a priority basis, the critical specifications and standards that address top level procedures and processes should be revised.

E.2.4 Manufacturing Technology Program

Manufacturing Technology Program should include concurrent engineering process improvements.

E.2.5 Focused DoD Technology Program

DoD should initiate a coordinated program that addresses the development of enabling technologies.

E.2.6 Pilot Programs

Services should initiate programs for the purpose of exploring changes in the acquisition process that will obtain the benefits of concurrent engineering.

E.2.7 Chain of Command

The chain of command from the USD(A) to the program managers is the critical path for making changes in the acquisition process. Education of the individuals in this path is a necessity if consistency and effectiveness are to be achieved. Affecting acquisition programs is clearly the objective. Actions taken by this chain of command are the most effective way to influence industry and consequently the most effective way to obtain the desired results.

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G. SPEAKERS

G.1 Workshop 1, 11-12 May 1988

Wednesday, 11 May 1988

Robert McCormack, Deputy Assistant Secretary of Defense for Production Support
> Welcoming Remarks

Don Clausing, MIT
> "The Quality Model"

Willie Hobbs Moore, Ford
> "Why Ford applied the Taguchi method"

Jack Katzen, Assistant Secretary of Defense (Production and Logistics)
> Luncheon Keynote Speaker

Mike Kutcher, IBM
> "Concurrent Engineering at IBM"

Jim Pratt, ITT
> "Characterization of a Company Practicing Concurrent Engineering"

Thursday, 12 May 1988

Don Clausing, MIT
> "Improved Total Development Process"

Bill Haney, Texas Instruments
> "Concurrent Design at Texas Instruments"

James Kowalick, Aerojet Ordnance
> "Results of Applying Concurrent Design at Aerojet Ordnance"

Kidar Chadah and Don Duboise, Northrop
> "Concurrent Design at Northrop"

Patrick Kelly and Tim Van Bibber, McDonnell Douglas
> "Concurrent Design at McDonnell Douglas"

G.2 Workshop 2, 25-26 May 1988

Workshop 2 consisted of several panel discussions. The panels were formed as follows:

Enabling Technologies

John Hanne	MCC	Chair
Rod Julkowski	Honeywell	
Bill Henry	Boeing	
Sarosh Talukdar	CMU	
Gene Seefeldt	Deere	
Alan Fulton	AT&T	

Luncheon Address Robert Duncan, Director, Defense Research and Engineering

Weapons System Application

John Halpin	USAF	Chair
Dave Altwegg	USN	
John Sheridan	Boeing	
Robert Schell	Aerojet Ordnance	
Don Snyder	McDonnell Douglas	
Jim Pratt	ITT	
Gordon Keefe	ASI	

Government Technologies Initiatives

Hal Bertrand	IDA	Chair
Phil Parrish	DARPA	
Howard Bloom	NBS	
Tony Woo	NSF	
Charles Church	Army	
Nate Tupper	USAF	

Will Willoughby presented his views of concurrent engineering and the recent improvements in the acquisition process within the Navy.

G.3

Two smaller working panels met during June to identify acquisition issues and technology challenges related to concurrent engineering. No papers were presented at the June sessions.

H. REVIEWERS

This report has been reviewed by a team within IDA, an expert external review panel, and 60 to 80 workshop attendees, and other interested parties. These participants are listed in Appendix F. The contribution of participants and reviewers has been substantial, but inclusion of their names should not be construed as an endorsement of this report.

H.1 IDA Reviewers

Cathy Linn, Joe Linn, David LeVan, Bill Akin, Terry Mayfield, Jack Kramer, Bill Cralley, Lane Scheiber, Dick Schwartz, Gary Comfort, Dave Randall, and Gen. William Y. Smith.

H.2 External Reviewers

The external review panel was chaired by Ruth Davis. Other members of the external review panel were Rex Bryce, Jacques Gansler, Mike Kutcher, Bob Lundegard, Jim Pratt, Bob Schell, Don Snyder, Myron Tribus, Jim White, and Yuin Wu.

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PREFACE

Task Order T-B5-602, under contract MDA903 84 C C031, directs the Institute for Defense Analyses to identify critical information and factors associated with the use of concurrent engineering in weapons system development as well as DoD and industry efforts that are potentially applicable to this effort. This report responds to a subtask that calls for a report based on the findings of a study of concurrent engineering including site visits to companies practicing it and is intended to be part of a larger effort. It contains a straw man approach to achieving concurrent engineering in weapons system development (Appendices D and E).

This report has been prepared by an IDA study team (the authors of this document) based on a preliminary study of concurrent engineering. The practice of concurrent engineering in the United States is an emerging discipline and validated models describing the functions and information requirements have not yet been developed. This report represents an initial attempt to define a conceptual framework for concurrent engineering, to describe the methods and techniques being used by those practicing it, and to list reported benefits of those attempts. It is anticipated that more complete models describing the functions and information exchanges of concurrent engineering will be developed in subsequent studies.

In preparing this report, the study team gathered information from individual industrial, academic, and corporate experts and from experienced corporations. The study team organized the information and made judgments about the validity and applicability of data and expert opinion. This report is based on those judgments.

The report was reviewed by internal and external panels whose members are listed in Appendix H. Workshop participants are listed in Appendix F. The contribution of participants and reviewers has been substantial, but inclusion of their names should not be construed as an endorsement of this report.

The authors acknowledge the contributions of many who helped to produce this report: the companies who provided success stories, the speakers at the workshops, and the workshop attendees who helped to shape the ideas presented in this report. This report would not be possible without their assistance and the support of their parent companies.

The study team especially acknowledges the contributions of Gary Ammerman, Charlie Bernstein, George Box, Don Clausing, Travis Engen, Alan Fulton, Larry Griffin, Istvan Gorog, George Gregurec, John Halpin, Bill Haney, Leo Hanifin, Bill Henry, Stuart Hunter, Ed Istvan, Mike Kutcher, Chuck Laurenson, Vern Menker, James Nevins, Mike Patterson, Madhav Phadke, Jim Pratt, Homer Sarasohn, Bob Schell, Gene Seefeldt, John Sheridan, Russell Shorey, Don Snyder, and Michael Watts.

The authors also express their thanks for the help they received from Helen Singleton, Diane Eason, and Chloie Boelte, as well as the editing assistance from Ellen Pennell and Katydean Price.